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RELATIONAL DATABASE COMPILED/STORED ON A MEMORY STRUCTURE

Abstract:

The present invention is first related to a relational database compiled/stored on a computer environment and adapted for access by application programs executing a query within said database and compiled/stored on said computer environment comprising: a first set of tables with first columns and tuples containing first data; a second set of tables with second columns and tuples containing second data; each of said second data being a redundant representation of at least one of said first data. The present invention is also related to a method for executing queries within a relational database, a database access system compiled on a computer environment, a clinical workstation implementing on a computer environment a representation of a group of processes, operations, services, acts, objects and persons within a hospital, and finally a hospital information system stored on a network of computer and workstations.

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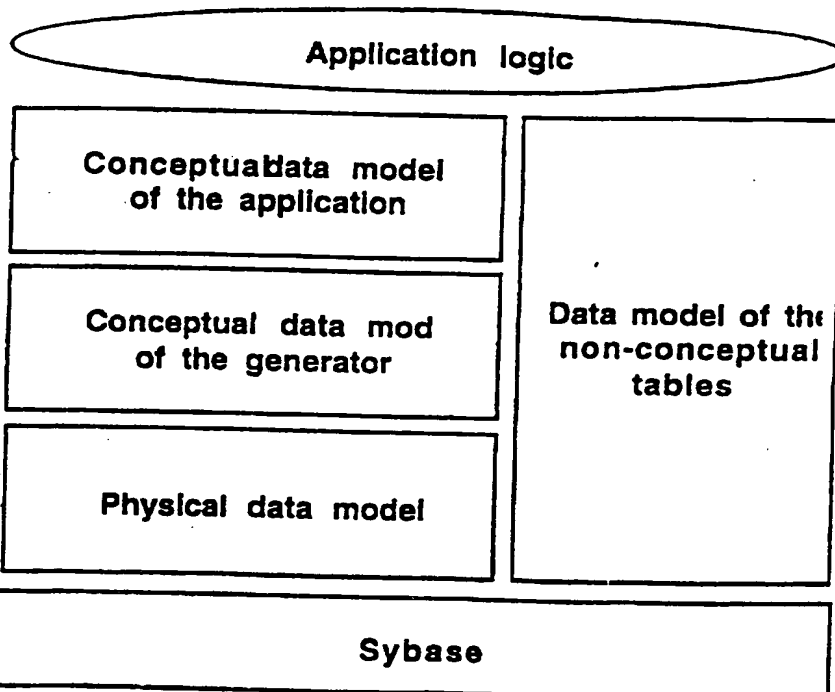
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(54) Title: RELATIONAL DATABASE COMPILED/STORED ON A MEMORY STRUCTURE

## (57) Abstract

The present invention is first related to a relational database compiled/stored on a computer environment and adapted for access by application programs executing a query within said database and compiled/stored on said computer environment comprising: a first set of tables with first columns and tuples containing first data; a second set of tables with second columns and tuples containing second data; each of said second data being a redundant representation of at least one of said first data. The present invention is also related to a method for executing queries within a relational database, a database access system compiled on a computer environment, a clinical workstation implementing on a computer environment a representation of a group of processes, operations, services, acts, objects and persons within a hospital, and finally a hospital information system stored on a network of computer and workstations.



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RELATIONAL DATABASE COMPILED/STORED ON A MEMORY STRUCTURE

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Field of the invention

The present invention is related to a relational database compiled/stored on a memory structure and adapted by access by application programs executing a query within  
15 said database.

The present invention is more precisely related to a system for developing software to be compiled in said computer.

20 Background of the invention

A database takes much of the burden of storing and managing data out of the application.

The advantages of using a database are manifold. The most important are: centralized control of data  
25 storage, sharing of data (between applications and users), centralized security, concurrency control, reduction of redundancy, ...

Database management systems are commercially available for virtually any computer platform. The  
30 technology has proven itself and it is cost effective to use a database. The alternative to using a database is using computer files to store the data. The application

becomes responsible for each of the database tasks mentioned above. Usually this option is only taken if there is no need for concurrency control, data sharing, security, ... This is almost only the case in single user  
5 (PC) systems.

There are several approaches possible in building a database management system, but the most important is the relational approach. Relational database management systems became commercially available in the late 1970s. Their main  
10 advantage over existing database technology was that they simplified the view the user had of the data. A very loose definition of a relational database management system is given as follows: a relational system is a system in which the data are perceived by the user as tables (and nothing  
15 but tables); and the operators at the user's disposal (e.g. for data retrieval) are operators that generate new tables from old. This definition looks at a relational database management system from the user's point of view. The actual storage format of the data is of course much more  
20 complicated. But this shows the main advantage of relational systems : the user only deals with the simplified view and is completely shielded from the lower level implementation structures.

The vendors of relational systems have  
25 standardized the way to access a relational database. Practically all databases support SQL (Structured Query Language). SQL is the language with which the user can create new tables from existing ones. SQL is a declarative language: the users specifies what data need to be  
30 retrieved and from what tables but not how they need to be retrieved. Since the user has no knowledge of the underlying physical data structures, it is impossible for

him to decide how the data should be retrieved. Therefore the system needs to translate each SQL statement into a query path. This specifies how the physical structures are accessed to retrieve the data.

5           Usually many query paths are possible for one SQL query. Almost all relational systems now have a component called the query optimizer. The query optimizer selects the path that will probably produce the desired result in the shortest time. To speed up the retrieval of data, the  
10 database administrator can define indexes. An index is a data structure that stores all values for a particular column in some table and keeps a reference to the rows containing that value. The values are stored in a structure that allows fast retrieval of a particular value. If a user  
15 wants to retrieve all the rows containing a specified value, the system can look up the value in the index, retrieve the references to the rows containing that value and use those references to directly retrieve the rows. This will be faster than scanning the whole table and  
20 checking each row for the specified value, because the index is smaller, the index is structured so that the relevant value can be retrieved without scanning the whole index. The main performance increase comes from reducing disk accesses. The disk is a mechanical device and is slow  
25 as compared to access to internal memory. Indexes are hidden from the user and the results of the query are the same whether the indexes were used or not.

          The query optimizer decides which indexes will be used and in what order. To take this decision the query  
30 optimizer takes into account the length of the tables, the availability of indexes, the selectivity of the index, .... It will always try to reduce the amount of rows to retrieve

as early as possible in the query. The selection of a query path is done using heuristics so it can not be guaranteed that the optimizer will produce the optimal path. As it will be seen later on, the optimizer often does not have  
5 enough information to produce the optimal path. This is often the case for complex queries and then one can aid the optimizer by splitting the query in smaller parts which are easier to optimize.

#### 10 Problem Definition

If a data model "shapes one's view and limits one's perceptions" then those limitations have to be as few as possible and the shaping should not be distorting. This shaping and limiting of the view of the world is in part a  
15 preferred effect : it structures one's world view and puts the focus on that part of the data to be manipulated using a computer. Therefore a data model is subject to three major forces :

- the desire to model a defined world of interest as  
20 completely as possible,
- the structure to impose on this model of the world, and
- the limitations of the level of complexity in relation to the hardware and the software.

With time reality changes as do one's views of  
25 this reality. For these reasons data models might have to be changed during the life time of an application. Updates of the data model are costly in terms of human resources. Thus a data model should also be time-resistant.

The model should also allow for any data  
30 structure to be entered since a limitation of what can be entered would also limit one's world view through the model. That way all information can be captured without

distortion and different models can be deduced from these raw data. The model is only deduced from the raw data. No part of the model is implied or enforced by the internal data structures since any type of structure can be entered.

5 If the model is only deduction this also makes it time resistant. To change the model one "only" has to change the deductions, not the data representation. Another advantage is that several models can be deduced (and used) at the same time on the same raw data. Since the data are truly

10 "raw", that is not distorted to accommodate the structure of the internal data representation, these data can be seen as truths or essences : somebody at a certain point in time has stated that X was true. Entering data is adding a message to a gigantic pool of messages. The world is

15 chaotic and the structure of the chaos to model is in the eye of the beholder. The problem is that the less information in the data representation, the more information needs to be deduced. If there is no structure inherent in the internal data representation this becomes a

20 gigantic task. One trade freedom of storage for complexity of deduction. Current database technology does not allow this freedom of storage.

Relational databases are state of the art but have a much more rigid storage format than described above.

25 In a relational database data are represented in the form of tables. A table has columns and the rows which are called records or tuples. So for each type of message a table is defined to store all the messages of that type. A message becomes a row in that table. Tables have to be

30 defined before data can be stored in them. This limits the freedom : to foresee which types of messages will be needed. Because the structures have to be created



beforehand, the users cannot add messages that where not anticipated. Using a query language the programmer can deduce new virtual tables (called "views") from other tables. A query is the deduction of a set of tuples (view) from several other sets of tuples (tables and views). A typical database can handle queries that use up to 16 tables, but a query with 16 tables will be far too slow to use in an on-line interactive system. This severely limits the level of complexity of the deductions possible for queries that require fast response times.

It is an option to choose data modelling strategy that captures all raw data. This is done in the form of messages. A message is the content of an electronic form. The messages are in essence statements or essences and have the implied generic form of "user X at time Y states that Z is true". This implies that the data model is additive: new information is added as a new message. Messages are never updated: a message that is true at a certain point in time will later always have been true at that point in time. A new message might contradict or supersede an old message but the statement the old message stands for, remains true. So updating is conceptually not allowed in this data modelling strategy. There is one reason why updates are allowed here : the user is fallible and might make a (typing) error when adding a message to the system. These errors need to be corrected. The solution is to send another message of the same type to the database and to state that the new message is a correction of the previous one. The old message is only logically deleted, i.e. in the deduction of the present model in most cases a message is ignored whenever there exists another message that corrects it. At the interface level the user can correct the content

of the electronic form and with one mouse-click send the new message. The system automatically omits the old version logically and links the new version to the old.

According to this option the database will grow  
5 while query performance degrades. This is a bottleneck related to unlimited database growth. The next bottleneck that will arise is recovery time. The larger the database, the longer it takes for back up or to reload it from tape in case of media failure.

10

#### Summary of the invention

In order to have a clear vision of the main characteristics of the present invention, several definitions are given hereunder.

15 Conceptual tables are tables of a first set of tables which can be modified by adding another tuple with data to the table.

Non-conceptual tables are tables of a second set of tables which can be modified by whatever action, e.g. :

- 20
- update of one column of a tuple
  - addition of another tuple
  - update/change of one tuple
  - deletion of tuples
  - etc.

25 In the present invention, data can be defined as :

- a tuple,
- a column,
- an element on the cross of a column and a tuple, or
- 30 - parts thereof.

Database management systems store meta-data, this is data about data. These data are kept in the data

dictionary. Typical meta-data are the types (character, integer, real number,...) for each of the columns in a table. Meta-data are used by the system to check for errors.

5                   Redundant should be understood as :

- a copy of data,
- a "derivation" of any data like :
  - an operation (multiplication, division, percentage, combination, verifying the presence of, ...) on any
  - 10     data, only using one data point,
  - an operation (multiplication, division, percentage, combination, verifying the presence of, ...) on any
  - data, using several data points (tuples, columns in the same table or in several tables).

15                   An application can be defined as a set of programs that integrate a specific functionality.

A service can be defined as any act that can be asked for or executed by a patient. For instance, a service type can be any act of radiology or nursing.

20                   Finally, a unit (or unit of work) is a unity of acts that are executed in a specific order (the unity is made by the unity of patient, the unity of treatment, the unity of service, ...).

The present invention is first related to a

25   relational database compiled/stored on a computer environment and adapted for access by application programs executing a query within said database and compiled/stored on said computer environment comprising :

- a first set of tables with first columns and tuples
- 30     containing first data;
- a second set of tables with second columns and tuples containing second data, each of said second data being a

redundant representation of at least one of said first data.

A second object of the present invention is related to a method for executing queries within a relational database, comprising the steps of :

- selecting tuples in said second set of tables, and
- reading out the tuples of said first set of tables corresponding to said selected tuples of said second tables.

10 A third object of the present invention is related to a database access system compiled on a computer environment, comprising :

- a relational database including :
  - 15 - a first set of tables with first columns and tuples containing first data,
  - a second set of tables with second columns and tuples containing second data, each of said second data being a redundant representation of at least one of said first data; said database being adapted for access by application programs executing a query in said database;
- 20 - meta-data; and
- means for optimizing the steps of accessing said database, said means comprising tools for retaining a set of meta-data after first data are inserted in said database, said set of meta-data verifying errors in an insertion of next first data in said database.

A fourth object of the present invention is related to a clinical workstation implementing on a computer environment a representation of a group of processes, operations, services, acts, objects and persons within a hospital comprising :

# INTERNATIONAL SEARCH REPORT

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A. CLASSIFICATION OF SUBJECT MATTER  
IPC 6 G06F17/30

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)  
IPC 6 G06F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 320 266 A (HEWLETT PACKARD CO) 14 June 1989 see abstract see page 2, line 1 - page 4, line 18	1-40
X	GB 2 172 130 A (OKI ELECTRIC IND CO LTD) 10 September 1986 see abstract see page 1, column 1, line 1 - page 2, column 1, line 48	1-40

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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# INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 0320266 A	14-06-89	JP 2002459 A	08-01-90
		US 5276870 A	04-01-94
GB 2172130 A	10-09-86	JP 1840903 C	25-04-94
		JP 61204733 A	10-09-86

- a relational database having :
  - a first set of tables with first columns and tuples containing first data, said first data being electronic messages being the contents of electronic forms wherein
  - 5       said first set of tables is organised as a set of generalized tables according to the different types of said operations;
  - a second set of tables with second columns and tuples containing second data, each of said second data being
  - 10       a redundant representation of at least one of said first data;
  - software modules, integrating a medically logical unit of said hospital.
  - a user interface including a dashboard and integrating
  - 15       said modules; and
  - a generator stored on said computer environment comprising :
    - first tools supporting a user interface;
    - second tools accessing said database;
    - 20       - third tools implementing said electronic messages and linking said database with said user interface whereby said messages are stored as data in said database and whereby said messages can be entered or accessed via said user interface.
- 25       A fifth object of the present invention is related to a hospital information system stored on a network of computers and workstations comprising :
  - a relational database stored on at least one computer of said network comprising :
    - 30       - a first set of tables with first columns and tuples containing first data, said first data being electronic messages being the contents of electronic forms;

- a second set of tables with second columns and tuples containing second data, each of said second data representing at least one of said first data;
- a generator stored on at least one computer of said network comprising :
  - first tools supporting a user interface;
  - second tools accessing said database;
  - third tools implementing said electronic messages and linking said database with said user interface whereby said messages are stored as data in said database and whereby said messages can be entered or accessed via said user interface; and
  - at least one clinical workstation comprising said user interface and modules allowing for entry of essences consisting of the group of processes, operations, services, acts and objects related to a patient's medical file within the hospital.

More particularly, the present invention will be described in relation of a clinical workstation and its integration within an existing administrative system to form an hospital information system.

It was decided not to build each application separately but to construct a basic software layer (the generator) on top of which applications were built. The generator consists of three main modules, one to handle the graphical user interface, one to handle database access and one to incorporate the basic user interface paradigm. This last module functionally ties the two other modules together.

According to a preferred embodiment of the present invention, the generator uses Sybase as database, Prolog as application language, MacWorkstation and later X-



windows for the graphical user interface.

The purpose of the generator is :

- to shield the applications from the underlying software components. This diminishes the dependence on them;
- 5 - to provide a higher level functional interface for these components. This allows faster application development since it allows to use larger building blocks;
- support for a basic user interface and data modelling paradigm. Including this in the generator causes all
- 10 applications to share these common features. This makes the system more user friendly and easier to master.

A new data modelling strategy is disclosed hereunder. This strategy discerns two types of data tables :

- 15 - conceptual tables are known to the application and its users. They model the world of interest.
- non-conceptual tables do not exist from a user point of view. They contain redundant data and embody an alternative data model.

20 Both performance and design benefit from separating tables in two classes :

- performance is enhanced by giving the non-conceptual tables a data model that facilitates those queries that are not performant when run on the conceptual tables.
- 25 Usually, only the minimal information necessary to speed up those queries are stored;
- design is facilitated because less performance compromises need to be made in building the conceptual data model. Using this technique the design for
- 30 expressivity is separated from the design for performance.

For the preferred embodiment of the present system application according to the present invention (called conceptual model of system 9), several specifications were developed :

- 5 - the data model is deletionless; that is, data are never physically deleted, only logically.
- the data model is additive. This means that updates are conceptually not allowed in the model. Data entry is seen as true statements (messages) from a user. The data model
- 10 is a set of tables to hold structured messages. Normally a message does not need to be corrected unless an error was made. Since the model is deletionless both versions of the message are kept when it is corrected.

The present system conceptual model according to

15 the present invention consists of three different levels :

- the physical level hosts all data whether logically deleted or not;
- the conceptual level is defined on top of the physical level and shows the current version of the messages. This
- 20 is the level the generator operates on;
- the application level defines the relationships between the messages.

These four data models (the three conceptual levels and the non-conceptual tables) form a meta-model.

25 The use of the meta-model facilitates reasoning over the global data model: the generator and the application operate on different levels of the conceptual model and performance problems are solved in the non-conceptual tables. Each model has a specific function in the whole of

30 the application.

During the development of the system, the electronic form was chosen as the basic interface object.

The user interacts with the system by sending and viewing electronic forms. This electronic mail-like metaphor matches well with a deletionless and additive data model. The basic form operations are implemented in the generator  
5 and do not need to be implemented in each application.

As an essential element in the user interface the dashboard was developed. The dashboard is the main instrument to navigate between different functions of the electronic medical record for a patient. It was developed  
10 for the first present system application, and was repeated in all subsequent applications. In a way the dashboard bundles the data for a patient and creates a virtual electronic medical file.

To solve the problem of implementing the  
15 diversity inherent to order entry, a generic tool is developed that it forms the basis for all order entry. Several subproblems were solved :

- an interface paradigm consisting of a selector, an editor and a collector was developed. These three items interact  
20 in a standard way in all order entry applications. Rule bases are used to steer the behaviour for specific functionality;
- the logical data structures used to represent orders in this system needed to be translated to the more rigid  
25 relational format. All structures are stored in a set of four tables by translating them to a canonical format using a rule base. Thus the diversity of order entry can be handled without creating an unmaintainable number of database objects.

30 The generator which is disclosed here supports the user interface metaphor and data modelling strategy. It is the basis for all three clinical applications

implemented. This demonstrates the general applicability of the tools and the metaphors used.

For the clinical workstation, it is identified the generic functionality that is needed in the clinical departments. This was implemented in the base modules. The specificity of each department was handled using rule-bases. Several software libraries to handle these rules were developed. The system was for instance applied in Paediatrics and afterwards in the Oncology, Gynaecology/Obstetrics and Ear-Nose-Throat departments. No major changes were necessary to the base modules to cater for the differences between those departments. All differences could be handled by adapting the rule base.

To avoid fragmentation of clinical data, a global hospital information system plan is required. This system should be able to handle both the administrative and the clinical data in an integrated way. A clinical workstation would need to be built or bought as an addition to the administrative system. The clinical workstation was to be the clinician's interface to the hospital information system. It should be able to capture clinical data at the source. These data should be the basis for an electronic medical record. The system should allow the use of data for management purposes at the departmental and hospital level.

25

#### Detailed description of the invention

The further textual specification assumes for the purpose of teaching only the implementation of a system developing software to be compiled on a set of computers and more particularly for a hospital information system stored on a network of computers and workstation.

30

Sybase was the one of the first relational database management systems to gear itself towards OLTP (On-line Transaction Processing). In OLTP applications many transactions are requested per second and the number of simultaneous users is high. Sybase pioneered some features that warranted its selection as the main clinical database.

The Sybase server consists of a single UNIX process. This means that all simultaneous users are catered for by this single process. The advantage is that this process can do an overall optimization of memory management and disk accesses for all user processes. Originally, most of the competition relied on several processes to implement the server. This left much of the scheduling to the operating system which is easier to implement but less efficient because the operating system has less information to base its scheduling on. The operating system does not "know" what the processes it schedules are doing and what their interaction is. By bringing all user processes into one server process, this server process can take advantage of the interdependencies of the user processes to schedule them.

With Sybase the client software is only a C library. This C library can be incorporated into the application program. All accesses to the database server are made via calls to programs in this library. The client software does not process data. It only sends the commands to the server and retrieves the resulting rows. All other processing is done on the server. This architecture allows to run the application and the database on different servers. The best results are obtained when Sybase has its own dedicated server, and all clients reside on another machine.

In Sybase SQL queries can be written as a procedure. Such a procedure can have parameters to pass attribute values to the query. Procedures can be compiled and stored on the server. To enhance expressivity, Sybase  
5 added procedural control statements (if ... then ... else; while loops) to SQL. This allows to some extent to write smaller programs as stored procedures on the server. There are several advantages to this approach:

- compilation and most of the optimization is done when the  
10 procedure is created. This speeds up retrieval when the procedure is called. For procedures that are called thousands of times per day this also reduces overall load on the database server;
- network traffic is reduced because only the procedure  
15 name and parameters are sent from client to server;
- more access control. Users can be allowed to execute stored procedures without giving them access to the underlying tables. This gives complete control over which queries the user is allowed to perform. If necessary the  
20 procedure can perform (complicated) authorization checks before executing the actual query;
- if the query is reformulated, the application does not need to be recompiled as opposed to (some implementations of) embedded SQL.

25 Triggers are a special form of stored procedure that are executed when an insert, update or delete is done on a table. Triggers are executed within the same transaction as the operation that fired them. Triggers can perform business rule checks and if the check proves the  
30 operation invalid, the trigger can force the transaction to roll back (i.e. to undo all changes since the transaction started). Triggers are extensively used to perform

consistency checks and to support the specific fields and tables of the present system data model.

Application development language and for the purpose of  
5 teaching only in the sequel is chosen : Prolog

A computer is programmed using a computer language. At the lowest level the processor executes instructions. The set of instructions that the processor can execute is defined by the manufacturer when the  
10 processor is designed. The manufacturer also supplies a language that uses these instructions to program the processor. Such a language is usually called an assembly language. Assembly language is hard to read and to program because it is a low level language. Its expressivity is  
15 low; that is, even simple programs require many instructions. Applications are rarely written in assembly language. Usually so-called third generation languages are used to program applications. A program in these languages is transformed (compiled or interpreted) into assembly  
20 language instructions which are then executed by the processor. Examples of third generation languages are Pascal, C, COBOL, PL/1 and FORTRAN. These languages are more expressive than lower level languages. All but non-trivial programs are much shorter in C or Pascal than  
25 they would be in assembly language. This means that the burden of part of the complexity of programming has been shifted from the programmer towards the compiler (or interpreter). The more expressive the language, the more complex the compiler or interpreter for such a language.  
30 The compiler or the interpreter needs to be more "intelligent" to be able to transform a program written in this language into an assembly language program.

Before the start of the project, the U.Z. Leuven used the third generation language COBOL in its administrative systems. At that time fourth generation languages were emerging. These were more expressive and compensated the increased complexity of the implementation by being more specific. They are usually very well integrated with relational database systems and very apt at retrieving and manipulating data from these databases, and come with a built-in graphical user interface. The main disadvantage of these languages is that they are owned by the company that built them, which makes them dependent on the financial fate and the commercial vagaries of the parent company. Another disadvantage is their specificity. The complexity of the implementation is reduced by making them more specific. Most fourth generation languages are geared towards database access. This makes non database computations often difficult to program (and the resulting program is usually not very efficient).

An alternative to fourth generation languages is Prolog. Its main advantages over fourth generation languages are :

- it is not owned by a single company, and
- it is a general programming language with high expressivity.

Prolog is often called a fifth generation language but this term is misleading. Prolog did not evolve from fourth generation languages but has its roots in logic. The language is an implementation of a subset of first-order-logic called Horn clauses. Many implementations of Prolog are available and as of June 95 an ISO standard is defined.



Prolog has become a performant language because most of the research into the optimization of Prolog is done by many universities and the ideas resulting from this research are then built into the specific Prolog compilers.

5 As with relational databases, there is competition between the Prolog vendors for the fastest Prolog. With a fourth generation language only one company can do all the work.

Prolog by BIM is used, which is both fast and robust. It has been decided at the start of the project to

10 do all developments in Prolog and to translate the time critical parts into C when necessary. This was never needed : the Prolog programs are sufficiently fast.

Prolog is not the "silver bullet" to solve the so called chronic software crisis, but it has some unique

15 features that make it easier to write programs with less bugs.

#### Memory management

A program manipulates data structures. Usually

20 the programming language has specific instructions to allocate memory to data structures that it wants to create. When the data structures are no longer necessary the program de-allocates the memory. A frequent type of bug is a memory leak. When a program does not de-allocate all the

25 memory it no longer needs, it may stop functioning when all memory is consumed. In large programs these bugs may be hard to find since the error (not de-allocating memory) does not immediately cause the program to fail. If the program does not run continuously the error may never be

30 detected since the program never exhausts available memory. In a clinical workstation that is operative day and night even a memory leak of one byte will eventually cause the

system to fail. In Prolog memory is allocated automatically and when practically all memory allocated to the program is used, a garbage collector is invoked. The garbage collector detects memory that belongs to data  
5 structures that are no longer needed and de-allocates it. This eliminates an important source of bugs.

#### No dangling references

Most programming languages use pointers. A  
10 pointer is an electronic reference to a data structure. If the structure has been deleted (due to memory de-allocation) or if the program wrongfully altered the reference, the pointer points to random bits or to another structure if the memory was re-used. This is called a  
15 dangling reference. This problem cannot occur in Prolog since Prolog does not use explicit references. All references are implicit and handled by the Prolog language internally. The programmer can manipulate data structures via variable names and does not (need to) know where the  
20 structure resides in memory.

#### The logical variable

Logical variables are variables that can be free (i.e. they did not yet receive a value) or instantiated  
25 (i.e. a value was assigned to the variable). Destructive assignment (i.e. re-assigning a value to an already instantiated variable is not possible. In most other languages destructive assignment is the rule rather than the exception.

30 The omission of destructive assignment facilitates debugging. In a large team people constantly use pieces of software written by other members of the

team. To put it simply, you give your data structures to somebody else's program that reads them (maybe alters them) and that creates some new structures for you. If the function is faulty, it may destroy your data structures, 5 your program will probably not notice this immediately but will encounter problems later on when it tries to do something with these structures. Depending on the alteration, the program may calculate wrong results or halt completely. In most languages, parameters are passed as 10 references.

Because Prolog does not allow destructive assignment any faulty data structure can only be created faulty and not be inadvertently damaged. This facilitates debugging since one programmer does not need to trust the 15 other programmer's functions : he cannot change his data structures.

#### Formal specifications

One of the methods to write reliable software is 20 to construct correctness proofs for each program. This is only feasible for very small programs and checking the correctness of the proof can be as tedious as checking the correctness of the program itself. Some languages try to overcome this by allowing pre- and post-execution 25 conditions to be specified in a formal logical way. Since Prolog is a declarative logical language the program is the formal specification. It is an executable specification. Although this is an oversimplification - Prolog allows some non-logical operations - large parts of the program can be 30 read completely declaratively. Especially the rule bases used to customize the modules for the different departments.

## USING ARTIFICIAL INTELLIGENCE (AI) TECHNIQUES

Prolog also allows to use Artificial Intelligence technology to build the present system environment as well as seamlessly integrating it with the general clinical workstation application. Many techniques developed in and for Artificial Intelligence were used. These techniques also make reliable, flexible and maintainable programs with shorter development times than with conventional languages. Some of these techniques are discussed here but it will be elaborated on their specific use when describing the software modules in which they occur.

### Rule based systems

A common technique in expert systems is splitting the software into an inference engine and a rule base. The rule base contains the knowledge about the domain in which the program is to operate. The inference engine is a sort of driver that knows how and when to invoke these rules. The main advantages of this technique are :

- it keeps the code small because the generic part is written only once instead of being embedded several times in the application specific parts. Enhancements to the generic part automatically benefit all specific parts;
- the knowledge is isolated from the solution-generating procedures. If something changes in the specifications of the problem only some rules will have to be added, deleted or updated. The application program code is not obfuscated by general program code and vice versa. Usually the rules (or groups of rules) can be reviewed independently from each other. This makes the program easier to maintain because the program lines that need to be changed to cater for an adaptation can more easily be

identified and isolated. Due to this isolation, errors made in rules tend to have only local effects : usually the other rules can still be used correctly and erratical behaviour is contained to a small part of the program;

- 5 - there is an implicit standardization since the generic part ("the inference engine") determines the structure of the rules. This standardizes the structure of all the application specific parts defined using those rules.

Since a Prolog program is itself a rule base,  
10 this technique comes very natural in Prolog. This design is taken a step further. When the knowledge can be split into several layers, one can reflect these layers in the program's design. The inference engine drives the use of a high level set of rules and some of these rules trigger the  
15 use of lower level rules. This allows minor changes to be performed at the lowest level of rules without having to changing the intermediary level of rules. Again the advantage is further partitioning of the program code and thus ease of maintenance.

20 This technique is analogous to what is called "data driven programming" in sequential programming languages. In Prolog, a program has the same structure as data. So the "data" that drive the program, can be programs themselves. This gives the leverage in software engineering  
25 needed for large systems.

#### Building custom interpreters

Another advantage of the similarity between data and programs is that one can manipulate Prolog programs the  
30 same way as Prolog data. Advantage is taken of this feature of Prolog to build the own limited interpreters.

Often the same type of program code needs to be written repeatedly during a project. If one can pinpoint the differences between these programs, it was found to be more cost effective to create a sort of special purpose  
5 "language" specific to the problem, and write an interpreter for it. The interpreter reads the program instructions in the new language and translates them.

This technique is used in a simple form. The "languages" created adhere to the Prolog syntax and thus  
10 can be represented by Prolog data structures. This made the manipulation of these structures by the interpreter trivial. Often this structure contained a list of high level commands to be executed. The interpreter reads this structure and selects the Prolog rules to trigger based on  
15 the information in the structure.

The advantage is that only the relevant parts of the code need to be written (the rest is generated). The program is shorter and easier to maintain. The disadvantage is that an interpreter needed to be written, but in Prolog  
20 this is much easier than in other languages. The point where the cost of writing the interpreter is offset by the gain of the automatic creation of program code is reached faster when using Prolog than when working with more conventional languages.

25 The Architecture of the data model according to the invention has several levels of data models which can be grouped into a meta-model (see Figure 1). There are four different parts to the overall data model. Three of these are built one on top of the other and the fourth (the  
30 non-conceptual tables) is a parallel model that is used at all three levels. Structuring the relationship between these data model levels facilitates the reasoning about

data during development. As described later on, most of the programs manipulate data at only one level of the data model. Each of these data models and their relationship to each other will be discussed, and finally, the use of the  
5 non-conceptual tables in optimizing performance will be demonstrated.

#### Physical data model

As mentioned above, the content of a form is a  
10 message. The physical model deals with the storage of these messages. Apart from the application defined fields, for each message a set of standard fields (a.o. who inserted the message and when) is added. These fields are also used to implement the support for the deletionless aspect of  
15 this level. This level is deletionless since no information is ever destroyed.

Whenever a user deletes a message, it is not physically deleted but only marked as deleted. The system also stores who deleted it and when. Whenever a message is  
20 updated (corrected), the update is translated in an insert of the new message and a delete of the old version. The system stores who inserted the new version and when, and links the new version to the old one. Figure 2 shows the standard fields needed to implement this data model. In  
25 every system conceptual table these fields precede the application specific fields. The function of each of those fields will be briefly described, and then it will be shown how they are used.

A unique number for each (version of) a message in a table. The *dkey* plus the table name uniquely define a message. The *dkey* is assigned by the system at insert time. The *dkey* and the sender are displayed in the right hand corner of the form to confirm the acceptance of the message by the database.

*omit* is one character with three possible values:

i : inserted: this is always the first value for this field

o : the message was omitted (logically deleted)

10 c : the message was corrected by another message.

*sender* and *sendTime*

*username* value of the person who sent the message and a *timestamp* value.

*omitter* and *omitTime*

15 These are initially null and will only get a value whenever the message is deleted. In that case they will contain the *username* of the person deleting the message and the time of deletion. At that time the *omit* field will be changed from 'i' to 'c'.

20 *cdkey*

Is only used if a message is a correction for a previous message. In this case this field will hold the *dkey* of the corrected message. This field "links" the new message to the old message.

25



*Example*

Suppose we have a table containing messages with only one application defined field called X. There are already two records in the table. One with the application content AAA and another with the application content BBB.

dkey	omit	sender	sendTime	omitter	omitTime	cdkey	X
1	i	Jeff	21.7.95 15:03:04				AAA
2	i	Ann	22.7.95 09:33:12				BBB

If Jeff now omits the message sent by Ann the table will become:

dkey	omit	sender	sendTime	omitter	omitTime	cdkey	X
1	i	Jeff	21.7.95 15:03:04				AAA
2	o	Ann	22.7.95 09:33:12	Jeff	22.7.95 09:35:14		BBB

If Ann corrects the message that was sent by Jeff (and changes the content from AAA to CCC, this update will be translated in an omit of the original message and an insert of the new message.

dkey	omit	sender	sendTime	omitter	omitTime	cdkey	X
1	c	Jeff	21.7.95 15:03:04	Ann	23.7.95 11:12:13		AAA
2	o	Ann	22.7.95 09:33:12	Jeff	22.7.95 09:35:14		BBB
3	i	Ann	23.7.95 11:12:13			1	CCC

The actual insertion of the username, timestamp, etc. in the System header fields is not directly done by the application programs but is accomplished using "triggers". The three basic operations (insert, omit and  
5 correct) can easily be initiated in a standard way from each electronic form. The electronic forms in the present system all share a standard header of icons. Each of the functions is linked to an icon in the header. The formTools module of the present system generator handles the  
10 processing of these functions for all forms in a generic way.

Due to the deletionless-ness, the physical level contains also a log of all versions of all messages. This has several advantages. The first is that whenever there is  
15 an argument as to what information was available at a certain point in time, the state of a message or group of messages that time can easily be reconstructed. Although only the programmers can query the physical level to retrieve previous versions of a message, some privileged  
20 users (the administrators) can retrieve a history of the versions of a message. This history lists who changed a message and when. If a user has questions about the version history of a message, the administrators can give him the names of the people involved. If necessary, the actual  
25 versions can also be retrieved and compared.

The second and most important advantage is that every user is responsible for every bit of information he enters into the database. This is also the reason why the dkey and the sender's name are shown when a form is sent :  
30 it reminds the user of the fact that the database has accepted the message and stamped with his name. The unique number identifies this version and any subsequent updates

can never erase this version. When changing or overwriting information in a written medical file, it can almost always be seen that some information was overwritten. In a computer this is not the case. The new version of a medical report looks as pristine as the previous one. This lowers the resistance to change information in an electronic medical record. The aim of the logging of all changes and the constant reminding to the users of this logging is to compensate for the lack of visual traces of the overwriting.

#### Conceptual data model of the generator

The basic layers of the present system software are called the generator. In the conceptual data model of the generator, the deleted messages and older versions are logically omitted from the tables. A table at this level contains only the last version of each message. This level is used in all application queries and the physical level is completely hidden (except for the version history query for administrators).

This level can easily be created by defining relational database views on top of the x# tables. By convention, the name of this view is the same as the underlying table but without the x# prefix. The definition of the view foo on top of x#foo is shown in Figure 3. The structure of these views are simple, thus they do not hamper performance. To all intents and practical purposes this view behaves as the conceptual base table for all higher level data models. Therefore these tables are called table-views.

Updates and deletions of messages should only be used in case of errors. This is only possible if the

application data model is an additive model. This implies that a message should contain information all of which is known at the expected time of data entry by a single user. The user must be able to send all the information as a whole to the database. E.g. if two information items A and B are not known at the same time, but operational procedures require the data entry of item A into the system, then item B cannot be part of the same message (and part of the same electronic form) as item A. If it would, the procedure would force the user to guess the value of item B (or to leave it blank) when sending the message. When item B becomes known, the user would then have to correct the message. Such a situation is considered a data modelling error for an additive data model. Again compromises have to be made to keep the system ergonomic. Taken to the extreme every data item could be a different message. This would avoid the problem above since one never has to send two or more items on one form. In an ideal world with infallible and omniscient users the content of this level should exactly be the same as the content of the physical level.

#### Conceptual data model of the application

This level is based on the conceptual model of the generator. This level defines the fields that hold the contents of the messages. An application data model defines an information stream. Each user (or function generating information) is localized somewhere on this stream. A user receives the messages from the people upstream and adds his information using electronic forms for the use of the persons downstream. This is exactly the same as with paper forms. A paper form is completed and then sent to the next

person in the information stream. This person will probably generate new information and send it (back) to the next person in the stream.

This data modelling strategy allows the users to  
5 take on a more active role in defining the data model. Usually the future are asked users to think as if they will re-engineer their procedures using paper forms. There are a few extra assumptions they are allowed to make because of the electronic nature of the forms :

- 10 - the forms arrive at their destination virtually immediately;
- a form can be viewed by several persons at the same time (there is no serialization necessary if two persons need the same information);
- 15 - parts of forms can be hidden for some (types of) users.

The users can build their data model together with the analysts, so they understand what the data model represents. This transparency allows them to deduce which information functions are possible and which ones are  
20 excluded by the data model. This contrasts with the more classical approach where the analyst extracts the specifications for the different functions that need to be accomplished by the information processing system, and subsequently builds a data model to support these  
25 functions. When the user changes the specifications or when new functions need to be added, it is possible that these do not fit well onto the data model. The data model then needs to be adapted, which is costly. By taking on a more transparent approach towards data modelling the user can  
30 guard compliance of the data model with his world view.

Benyon states that a data processing model is built from a data model and a process model. The data model

represents the structure of the enterprise by modelling it in terms of objects and relationships between those objects. The process model focuses on the transformations which take place in the system. These processes transform  
5 the data through some manipulation, re-structure it more usefully, or relate it to other data. The data model and the process model respectively represent the static and dynamic features of the information model.

Mapping one's data modelling technique on this  
10 type of data modelling, one could say that the process model is highly simplified. Processes in the real world result in only one type of change in the database: the addition of a message. No data are manipulated or restructured by any user originated function. This  
15 simplification adds to the transparency of the data model. As stated before, this simplification in data entry and manipulation leads to more complex deductions. So the price to pay is performance. This is solved by trading deduction performance for storage space and insertion performance as  
20 explained in the next section.

**Non-conceptual tables (application level) optimize performance**

The message modelling technique treats a business  
25 process as a flow of messages. The status of a business process can be deduced from the presence and absence of messages. As an example, 5 of the messages involved in an outpatient visit are examined. A reception form is filled when the patient arrives (1). Then the patient is assigned  
30 to an assistant and a supervisor (2). The assistant will write a report after the visit (3) and the supervisor will validate this report (4). The secretary mails the report to

the (external) doctor who requested the examination(5).

Each of these messages can be sent by a different person. The messages have to be sent in this sequence. It is obvious that one cannot validate a report that does not  
5 exist but the system will also check that a report cannot be written if the patient is not assigned to an assistant and a supervisor. For each outpatient visit all four forms have to be completed (allowing a number of exceptions). The five phases describe a unit of work.

10           The status of this unit of work called "ambulatory care visit" is the progress through these five phases. The phase the patient is in, and the next step to do, can be deduced from the presence and absence of the messages. This way the system will make worklists to show  
15 the users the specific information necessary to accomplish their work. E.g. the assistants will want a list of all patients that have been receptioned but not yet assigned. They will start from this list to divide the work among them. After assigning patients (sending the electronic  
20 assignment form) they will see and treat the patient. Later the assistant uses a list of all patients assigned to him but for whom no report is written yet, to start writing the medical reports. The supervisor will want a list of all unvalidated reports for patients assigned to him.

25           Each of these work lists is defined as a view in the relational database. The structures of these views are similar: they select patients for which a particular message exists and another message does not exist. Only a small part of the tuples in each of the tables will  
30 participate in these queries, namely the tuples pertaining to units of work for which not all five phases have been completed. These units of work are said to be in

production. Most of the data will be on units of work not in production: data about visits that have validated reports.

For the work lists mentioned above most of the  
5 computational work is of the type "find tuples from table A for which there isn't a tuple in table B". For real life queries obviously more than two tables will participate in the query. The performance of the query will deteriorate as the size of the tables grows. In a medical setting  
10 historical data are so important the users want to keep information on-line as long as possible. This means that as the database grows performance will degrade. Two types of tables can be discerned : static and dynamic tables. Dynamic tables grow in size at approximately the same rate  
15 as units of work are added to the database. E.g. the report table is a dynamic table: for each visit of the patient to the hospital one or more reports will be written. Static tables grow at a much slower rate, which is usually not linked to the amount of units of work. E.g. a table of  
20 definitions of radiological examinations will grow as more techniques for medical imaging or new machinery becomes available. Other examples are the tables containing doctor identifications, ward numbers and descriptions, medication lists,... . These tables also grow, but several orders of  
25 magnitude slower than the dynamic tables. They usually contain hundreds or a few thousand records.

Queries (like work lists) used to support the normal workflow are called production queries to discern them from management queries. Production queries need fast  
30 response times to assure a smooth workflow. Production queries can be divided in point queries and set queries.



Point queries are queries that give all tuples pertaining to one known entity and has an indexed identifier. E.g. all reports for a single patient; or all assignment forms for a single supervisor. Set queries range  
5 over several entities and are usually of the work list type as described above. Point queries can be speeded up using indexes that are available in any commercial database system. Set queries also benefit from indexes but these are not sufficient to reach the required performance level. The  
10 solution found for this problem was using extra tables to store the information needed to speed up these queries. These tables contain only redundant information and do not exist from a conceptual point of view. Hence the name non-conceptual tables. Status tables are non-conceptual  
15 tables containing information about the status of a unit of work. The non-conceptual tables make up an alternative redundant data model. It is a compressed data model since only the redundant information needed to speed up the selection of the relevant units of work needed in queries  
20 is stored. In a way the non-conceptual tables act as semantic indexes to the data in the conceptual tables. Once the relevant units of work are identified the actual data are retrieved from the conceptual tables.

To optimize the ambulatory care example, a status  
25 table should be needed with four attributes in addition to the four tables containing the messages for the reception, assignation, report and validation form. In this status table visitID contains the identification number of the visit, assigned contains 0 or 1 indicating the existence of  
30 an assignation form for this visit. Report also contains 0 or 1 indicating the existence of a medical report. Whenever a new unit of work starts, a record is created in the

status table (see figure 4a)

The tuple above indicates that a visit with identification number 7 is in production and that only the reception phase has been completed. When the visit is  
5 assigned to an assistant and a supervisor, the assigned bit is flipped from 0 to 1 (see figure 4b).

When the medical report is sent to the database the report bit is flipped. When the report is validated the next bit is flipped. When the "sent" message is added to  
10 the database the record for that visit is deleted from the status table. Sending is the last phase so the unit of work is no longer in production. The status table contains information on all visits :

- all visits not represented in the table are out of  
15 production;
- the visits that are in production can be in either of four states :
  - receptioned only
  - receptioned and assigned
  - 20 - receptioned, assigned and reported upon
  - receptioned, assigned , reported upon and validated (i.e. no status record is present).

Time is also represented differently. In the non-conceptual tables time progress is represented in the  
25 columns : as work for a unit of work progresses, values in the columns are updated. In the conceptual tables, time progress is represented in the rows. Completing a phase in a unit of work means adding a rows to a table (see Figure 5).

30 The status table allows to rewrite queries that test for the existence of messages and make them more efficient. Assume that all visitIDs and patient names of

visits that still needed to be validated by supervisor A are wanted. Without the status table this means going through the "assigned" table and for each visitID assigned to supervisor A go through the report table and check for  
5 the existence of a report with the same visitID. For each of those reports, check in the validation table whether they are already validated or not. For those for which no validation tuple exists, retrieve the patient name from the reception table.

10 Both the "assigned" table and the report table are dynamic tables. Most of the records in the assigned table have validated reports since only a limited set of all data will be in production. So the existence test for a record in the validation table will most of the time find  
15 that the report is already validated.

The same query is much faster to compute using the status table. Since it is very much smaller, it allows to find the units of work that are still in production much faster. This will be shown in the following experiment  
20 which is part of the query that supervisors use to retrieve the list of reports they have to validate.

#### **Experimental proof of performance gain**

As an example (a part of) the query to retrieve  
25 the validation list for a supervisor in the clinical workstation is shown. The query retrieves the list of reports that need to be validated by the supervisor assigned to handle that unit of work (i.e. a patient contact).

30 In the case of the supervisor used in the example, the query returns 6 rows (i.e. 6 reports need to be validated).

Six conceptual tables take part in this query. A short description of these is given in Table 1. In an experiment, 3 versions of the same query were shown and their performances were compared. The first version is a straight declarative implementation of the query. The second version uses the non-conceptual tables to enhance performance. The third version does not use the non-conceptual tables but is written more procedurally to help out the optimizer.

To compare performance, the time spent in evaluating the query and the number of times each table was scanned to find the solution were measured. The query optimizer can choose to access a table more than once because it does not find it optimal to do all data retrieval in one access. Usually the table will be scanned several times during one access. Sybase allows to print out the order of accesses (the query plan) but it does not tell which data where retrieved in each access.

#### The version

The first version does not use the non-conceptual tables. The query is written as one declarative select statement and all optimization is left to the query optimizer (see figure 6). The query optimizer only has syntactic information and thus does not "know" that most of the reports in the report table will be validated ones. The order of accesses and the use of an index in the access is listed in Table 2. The complete query plans for all three queries are listed in Table 3. From the order of accesses, it can be seen that the server chose a path in which it needs to access the x#verslag en x#validatie tables several times before it has identified the units of work that are

relevant. Once these are identified, it accesses the other tables to retrieve the attributes that need to be displayed.

In Table 4 the performance results are listed.  
5 Query 1 took 129 seconds to complete. Most of the time was spent in scanning the x#validatie table to resolve the "not exists" test in the subquery.

#### Version 2

10 The second version of the query uses the status table and is listed in Figure 7. The status table not only stores flags to indicate which phases have been completed but also the identification of the supervisor and the assistant to whom the unit of work is assigned. This means  
15 that both the selection based on the supervisor and the selection based on the existence of a validation can be done simultaneously on the status table. The name of the patient is also stored (redundantly) in this non-conceptual table since almost all production type queries need to show  
20 patient names.

As in query 1, this version is written as a single select statement and all optimization is left to the optimizer. An optimizer always tries to reduce the number of tuples to be processed as early as possible in the  
25 query. The optimizer has no problem identifying the optimal path for this query. It has three selection criteria (s.usernameSup = "x163646", s.verslag = 1 and s.validatie = 0) on the statusContact table which also happens to be the shortest table. From this information it surmises that the  
30 biggest reduction in tuples to be processed can be gained from accessing this table first.

This results in dramatic speed increase (elapsed time less than 0.5 sec). As can be seen from the query plan in the appendix, the query now accesses first the statusContact table using the index on supervisor, immediately identifies the 6 units of work that are relevant and accesses the x#S9User and x#verslag table to retrieve additional attributes not present in the status table. The number of table scans is thus greatly reduced.

The problem with query 1 is that the optimizer builds a non-optimal plan. Its heuristics can only use information from the structure of the query, the length of the tables and the presence or absence of indexes. It cannot use the semantic information that the application programmer has. In the case of query 1, the optimizer takes the wrong decisions and becomes a "pessimizer". In such cases an application programmer can increase the performance by enforcing a more optimal execution order. This is usually done by splitting the query in parts. The query optimizer will still optimize each of these parts but cannot change their execution order. Some of the advantages of SQL are lost this way. The query is harder to read, takes longer to write and if the length of some of the tables changes fundamentally, the optimization has to be redone. Nevertheless, this technique is often unavoidable for very complex queries.

### Version 3

The third version of the query does not use the status table but is optimized by splitting it in three parts (see Figure 8). The first part creates a table containing the identifiers for the units of work assigned to the supervisor. In the second part, all tuples

pertaining to units of work that are already validated are deleted from this table. With the resulting identifiers, the other tables are accessed to retrieve the attributes that need to be displayed. This sequencing of the computation is imposed because it is known that only a small percentage of the reports needs to be validated. Because semantic information is used (which is unknown to the query optimizer), this optimization technique is called semantic optimization.

10           This query is much faster than query 1 but still more than 7 times slower than the query using the status table. Although the number of scans has been dramatically reduced, the first two-parts of the query that identify the relevant units of work have more processing to do than  
15 using the status table : the x#validatie table needs to be scanned for all reports that are assigned to supervisor "x163464".

          Query 2 is by far the fastest query especially if one looks at the CPU time. In query 1 CPU time nearly  
20 equals elapsed time. This means that the query is CPU bound : the CPU is the bottleneck. Query 2 needs less than 100 ms CPU time (Sybase reports CPU time in units of 100 msec) so most of the 446 msec is spent waiting for disk access. The actual processing is very light. Query 3 is  
25 situated in between. Apart from the performance advantage, query 2 also is much more readable than query 3.

          As the number of units of work in the database increases, the performance of query 1 and 3 will deteriorate since both of them need to scan tables that  
30 grow with the number of units of work. Query 2 scans the statusContact table. This table will remain in a steady state if the workload on the department does not change

fundamentally. The number of accesses to other tables does not depend on the total number of units of work in the database but on the workload of the supervisor which will also be in steady state. The actual accesses to these  
5 tables are indexed accesses and thus only deteriorate logarithmically with the response time.

Using non-conceptual tables is trading in insert time and disk space for shorter query time. The redundant tables are kept up to date and synchronized with the  
10 conceptual tables using database triggers. Inserts become slightly less performant because at insertion time redundant data have to be updated or added in the non-conceptual tables. This is analogous to indexes. These also contain redundant data, and adding indexes to a table  
15 slows down insertions but speeds up queries. Because triggers are used to maintain the non-conceptual tables no extra overhead is placed on the application or on the network traffic between the client and the server. All overhead is on the database server.

20 At the start of a unit of work (e.g. the reception form in the experiment above) the insert in the reception table also causes an insert in the status tables. All subsequent phases in the unit of work cause updating one or more fields in the corresponding record in the  
25 status table. Usually an insert causes numerous checks to be done by the database server. E.g. when an assignment is made to an assistant and a supervisor, the system will check if the identifications in the assignment form exist in the identification table for MD's. If one orders a  
30 radiological examination, the system will check if this type of examination exists. Often several of these types of checks will take place during the insert process. Usually



an insert takes a few milliseconds so the additional overhead of maintaining the non-conceptual tables is negligible for the end users.

The other price to pay is disk space. The  
5 overhead here is low (see Table 4) and decreases as the database grows because the ratio of units of work in production versus historical units of work decreases. The number of records on a status table remains relatively constant when the department is in a steady state, that is  
10 it finishes as many units of work as it starts. There may be some fluctuations in the number of units in production (seasonal changes, shortage of personnel, ...) but eventually a steady state has to be reached.

What is gained is query response time as  
15 illustrated in the example above. Since a message is inserted once but queried many times the benefits clearly outweigh the costs.

A relational database not only optimizes the query paths but also memory management. Often used data are  
20 kept in main memory because the server anticipates that they will be used again and wants to avoid the overhead of disk access to retrieve them. Since most of the production queries use the status tables and most of the users use (only) production queries in their daily routine, the  
25 status tables are constantly accessed. Because they are small they can reside completely in memory. This has an additional positive effect on query response times because most of the accesses to the status table will only be logical reads (only in internal memory) and no physical  
30 reads (disk access).

In conclusion there are 3 reasons to keep the status tables small :

- the less redundant data there is, the less synchronizing needs to be done at insertion time.
  - the smaller the status table, the more chance there is it will stay memory resident.
- 5 - use of disk space.

At current disk storage prices the third reason hardly plays a role anymore. The first two have to be offset by the gains in query performance.

#### 10 Separating design for performance from design for expressivity

Maybe the biggest advantage of using non-conceptual tables is that less compromises need to be made in the conceptual data model to ensure performance. In  
15 the present methodology, the design for representation and the design for performance are split over different data models. This gives much more freedom in the representational aspects of the data model. The conceptual tables are externally visible through the functions in the  
20 system. The non-conceptual tables are invisible to the users. If in time the query patterns change and other functions need to be optimized, non-conceptual tables can be added or changed easily and then rewrite the queries to be optimized to use these tables. The data model as the  
25 users see it, remains unchanged.

#### Recovery time

The non-conceptual tables allow the database to grow while query performance degrades only with the  
30 logarithm of the database size. This removes one bottleneck to unlimited database growth. The next bottleneck that will arise will be recovery time. The larger the database, the

longer it takes for back up or to reload it from tape in case of media failure. Although this is a much less stringent constraint on database growth, it cannot be ignored. For each of the databases, it must be determined  
5 which is the maximum recovery time allowed. This, in combination with the maximum backup-and-restore bandwidth, will determine the maximum size of the database.

#### Effect on database size

10           The amount of corrected or omitted messages varies greatly from table to table. E.g. the assignment form for patients on a ward is corrected each time the physicians are assigned to new wards. The reports table  
15 contains many logically deleted reports since even a minor correction like for a typing error causes a copy of the report to be saved. All overhead in other tables is dwarfed by the overhead in the reports table: not only is this the  
20 table with the highest number of corrections, it is also the table with the biggest rows. Each report text field takes up at least 2 kilobytes

#### Architecture

Where the clinical workstation is used in direct support of the clinical work, X-terminals are preferred for  
25 their robustness. On private desks or for secretaries a personal computer is more suitable. Robustness is less of a problem here. These machines are usually less critical to the operation of a department than e.g. the clinical workstation in an operating theatre or a nursing ward.

## Hardware architecture

### Conceptual network architecture

The conceptual hardware architecture of the present System consists of three layers: a presentation  
5 workstation, an application server and a database server. These are connected by a network and act as a single system (see Figure 9). For each of the three conceptual tiers different physical machines are used. This allows to choose  
10 a hardware configuration for each tier that is optimally tailored to its function.

### PRESENTATION WORKSTATION

The presentation workstation only runs the presentation software and holds no application logic. No  
15 "programming" is done on this machine. This is the machine on the desktop with which the user interacts. The system needs to be capable of running a graphical user interface but should be controlled by programs on the application server. For the first two implementations of present System  
20 (Surgical Pathology and Radiology) Macintoshes were chosen as presentation workstations. The Macintosh was at that time (1990 and 1992) the most cost effective system capable of running a graphical user interface: it had a graphical operating system, networking was built in and it was easy  
25 to administrate.

As already mentioned, X-windows was chosen as the user interface software for the clinical workstation. This software can be run on PC's, Macintoshes or specific hardware called X-terminals. These are "intelligent"  
30 terminals capable of running a graphical user interface but without the need to store local software. X-terminals look like workstations. They have a processor and internal

memory but no hard disk. When an X-terminal is started up ("booted"), it connects to a host computer which uploads all the necessary software. This is the reason why no local hard disk is needed. They are also easier to administer since, after installation, hardly any local interventions are needed. The X-terminal has a local processor and memory but this is only used for the processing and data storage needed for the presentation software. The absence of a hard disk and lack of local software makes the X-terminal much more robust than a personal computer. These machines rarely crash since they have no moving parts. If they crash they can be swapped for a similar model without much effort since no local files need to be transferred from the old machine to the new one. The cost of client-server solutions is much higher if one works with personal computers as compared to X-terminals. By '93 the cost of an X-terminal was higher than that of a Macintosh, but the difference was so small that it was offset by the cost of migration halfway through the project.

While the X-terminal lacks the disadvantages of a PC, it also lacks the advantages of the PC. No local processing is possible and the standard office automation packages that are widely available on personal computers have no real counterparts on the UNIX machines that usually acts as hosts to the X-terminals. The X-windows software that runs on the X-terminals, can also be run on personal computers. In those places where one workstation is used both as a front-end to the hospital information system and for office automation, a Macintosh is placed with X-windows software. Since the application server converses with the presentation software via the X-windows protocol, no additional programming needs to be done on the application

server to support this configuration.

#### APPLICATION SERVER

The application server runs the present System  
5 environment. All application programming (with the  
exception of stored procedures, views and triggers) is done  
on this system. The application server controls the  
presentation workstation via the X-windows client software  
and is a client to the database server. Only transient data  
10 that are not shared by multiple users is stored on this  
system. This allows to have many application servers  
because each can function independently from the others:  
all data that need to be seen by other users is sent to  
the database server and all application servers are  
15 connected to it.

The application server executes CPU intensive  
tasks. Events from the windowing server trigger some Prolog  
programs. This results in issuing commands to the windowing  
server. Sometimes data from the database server will be  
20 retrieved. But no large amounts of data are processed on  
the application server. The disks on this machine are only  
needed to store the operating system (and other software  
necessary to exploit the machine), the programs for the  
clinical workstation and swap space. Each Prolog process  
25 requires on average 22 Mb of virtual memory. The ratio of  
physical memory over virtual memory is influenced by the  
expected number simultaneously active users and the number  
of functions in the application. The more functions in the  
application, the smaller the procentual part of the program  
30 that will constantly be used: a user can only do a few  
things simultaneously. Since each user has a specific task,  
he or she will only (repetitively) use and keep using a

subset of all possible functions. This is called locality of function. A receptionist will fill in reception forms and continue to do so for most of the time. Due to locality of function the part of the program that is needed in  
5 physical memory (the resident set) will not change during the use of the application by the same user.

#### DATABASE SERVER

The database server runs only the server part of  
10 the database. On this machine all data that are shared between users is stored. There is only one database server for all application servers. The database server receives SQL commands from the applications via the Sybase client software. No System programs run on this machine but some  
15 application knowledge resides on this system in the form of database triggers (used for consistency) and procedures (mainly used for reporting).

By using a separate machine as database server, its configuration can be tailored optimally to its use. The  
20 database server handles large amounts of data so this machine needs to be able to handle large volumes of disks. Most manufactures have machines in their product lines that are specifically geared towards database operations.

#### 25 Example of the processing of an event in this three tier architecture

Suppose a user presses a button on a dashboard to retrieve the medical report linked to a particular hospital stay (see Figure 10). When the user presses the button (1),  
30 the X-windows server detects this event. (2) The windowing server notifies - via the network - the windowing client on the application server of the event. The client triggers

the execution of the program written to handle this event.  
(3) The program will prepare an SQL statement to retrieve the report. (4) A Sybase client function is used to send the SQL - again via the network - to the Sybase database  
5 server. (5) The database server executes the SQL statement, retrieves the data from the database and (6) sends them to the client. (7) The present System program on the application server uses several Sybase client functions to read out the data. (8) Using X-windows client functions, it  
10 creates a report window on the X-terminal (via the network) and (9) displays the data using this report window.

#### Physical network architecture

In reality, the three types of computer are not  
15 connected to each other serially. The physical network architecture uses a backbone Ethernet network to which the application servers and the database server are connected. These reside in the Main Equipment Rooms (MER). From the MER fiber optic links are made to Satellite Equipment Rooms  
20 (SER). This is called the "vertical" cabling. A SER is a small room containing a patch panel. Each network outlet is connected point-to-point to the patch panel in a nearby SER. This is called the "horizontal" cabling. A universal cabling system is used for this connection. By making minor  
25 changes at the outlet and placing the appropriate active components in the SER, these cables could be used to support the most common network and terminal protocols (Ethernet, token ring, AppleTalk, RS 232, IBM 3270, ....). The active components in the SER are connected via vertical  
30 cabling to the servers in the MER.

The main advantage of this cabling system is that a building can be cabled when it is constructed. It is not



necessary to know the type of network connections in advance. Also, no cables have to be replaced if network services need to be changed for a particular room. E.g. if a user changes from a terminal to a PC or X-terminal, his network outlet needs to be reconnected in the SER to another active component. Possibly the external plug needs to be changed. The cabling needs no changes.

Upgrading the network to handle higher throughput (e.g. switched Ethernet or ATM) will be done the same way.

10 The disadvantage is that to keep the system universal some constraints have to be taken into account. The distance between the SER and the network outlet cannot exceed 100 meters and has to be a point-to-point connection. This means that enough network connections need to be foreseen

15 for each room since it is not possible to connect a workstation via another workstation.

#### The scaling of the present System

Since present System will take a few years to install hospital wide, the system will need to be scaled during that time. The effect of scaling on the three tiers of hardware will be examined. Three dimensions of scaling are considered :

- the number of users,
- 25 - the size of the application (as the number of functions grows, the amount of program code will grow also), and
- the amount of data stored.

It will now be investigated what needs to be done on each of the hardware levels to accommodate the growth in

30 each of these dimensions.

## PRESENTATION WORKSTATION

This is the easiest level to scale: one is added per workplace. The amount of data in the database does not influence the parameters of this workstation because the user will always require lists of a length that can be read on screen. It is no use to let the report lists grow as the amount of data in the database grows.

The same holds for the size of the application. While the number of windows that can be opened might grow, the number of windows simultaneously opened by a user is limited by what is ergonomically acceptable. If too many windows clutter the desktop, the user will close them automatically.

For a given a type of function, adding more functions will not require a more advanced workstation since the user is the limiting factor and he will only use a small subset of this larger whole simultaneously.

## Application server

The application server also scales trivially with the number of users : each type of application server can accommodate a certain amount of users depending on its processing power and internal memory. Adding users means adding or expanding application servers.

If the size of the application grows, more virtual memory will be needed per user since more program code and more data structures need to be stored in memory. Either more memory is added or more application servers are installed (adding both memory and CPU capacity).

The amount of data stored does not influence the application server since these only pass through the application server which formats them to be displayed on

the presentation workstation. Since the data are not stored and the number of records will automatically be limited by what can still be handled by the users, the amount of data that needs to be processed by the application server will  
5 not increase with the length of the database.

#### DATABASE SERVER

The database server needs to be scaled with the number of users: more users means more simultaneous queries  
10 and transactions. Both memory and processing power will need to be added. Database servers do not scale linearly by simply adding hardware.

The size of the application alone does not influence the load on the database server: the users will  
15 have more ways to view the same data. This might result in more usage of the computer but, since a user can only do one thing at a time, this increase will not be significant.

If the amount of data increases significantly, more disks need to be added and probably more processing  
20 power and memory (if the response times of the queries are to be kept constant). The query performance scales logarithmically with the size of the tables due to the present data modelling technique. The data modelling technique does not solve the problem of multiple users  
25 simultaneously doing updates in the database. More users and more data need to be offset by adding hardware and smarter database algorithms.

It is expected to have at the most 1000 concurrent users in the present System. This can be handled  
30 already by current technology. Database vendors are improving the parallelization of their servers and computers with 10 and more processors are state of the art.

Therefore it is possible to scale a database to more than 1000 users.

In conclusion, scaling the present System comes down to scaling the back-end database server. All other  
5 levels scale linearly by adding hardware.

#### Software architecture

To separately develop applications for all departments in the hospital would require too much  
10 resources. The implementation time for the whole of the hospital would be unacceptably long. In order to speed up development, it is decided to develop a set of generic software modules first to serve as larger building blocks for subsequent applications. The software developed at the  
15 U.Z. Leuven can be divided in 4 groups : the System generator, the System tools, the builders and the clinical workstation modules. The Surgical Pathology, Radiology and clinical workstation modules all share the generator and System tools as basic building blocks.

20 The first three types of modules are generic modules and will be discussed here.

#### The System generator

The System generator consists of three modules  
25 that closely interact with each other. It provides a higher level interface to Sybase and X-windows and implements the concept of forms on top of a deletionless database in a generic way. The generator is not specific to hospitals.

In Figure 11, is represented the data ship  
30 between presentation and database. In an application, data are constantly shipped between the screen (the front-end, in the present case X-windows) and the database (the

back-end, in the present case Sybase). In between, formatting, manipulation and checking of the data is done by the application. Procedures are specially structured application parts used solely for checking data integrity.

- 5 The generator provides tools to do much of this shipping between front-end and back-end. Because of the use of the form metaphor, all parts of the application related with forms can be handled in a generic way.

The three modules are :

- 10 - motifShell,  
- messageTools and  
- formTools.

Their interaction is shown in Figure 12. Modules can use lower modules but not vice versa. E.g. the  
15 application can use formTools, which in turn uses motifShell, which uses X-windows to display data on the screen, but motifShell can never call functions from formTools.

## 20 MOTIFSHELL

MotifShell is used to handle all presentation tasks in the present System applications. Roughly the module serves three purposes:

- a Prolog interface to Motif/X-windows,  
25 - implementation of high-level interface objects, and  
- speed-optimization.

By having a generic module to handle these tasks, it is avoided having to redo this for every program or application, and the access to the X-windows presentation  
30 package can be standardized, thus facilitating maintenance.

### Prolog interface

The first purpose of this module is to shield the System programmer from the low level details of X-windows. All X-client functions have their Prolog counterparts and these are used in application programming. It is the Prolog version of the X-windows client software. Apart from this low level functionality, motifShell provides powerful high level predicates that automate part of the work of creating and managing windows in X-windows.

10           The creation function of the window is generated by a tool called Builder Xcessory (BX). This tool is used only to design the window ("paint"). Only the resources needed to determine the type of widgets and their positional interactions (alignment to each other, 15 determining which widgets manage other widgets) are set using BX. These are resources that are relatively fixed in time and that will need little maintenance. All resources that will probably need maintenance in the future are set in the Prolog application. This allows to generate the 20 creation function with BX, link it to the System application and almost never touch it anymore. All maintenance can be done on the Prolog level.

To speed up application development, a small interpreter was constructed to allow the setting of 25 resources on a higher conceptual level. For each type of window ("shell") a data structure must be defined. This data structure contains high-level instructions to set or modify window parameters (see Figure 13). A small program reads these and for each instruction there are one or more 30 rules determining what low-level instructions need to be executed. One instruction can result in the execution of several low-level X-windows client instructions. Prolog is

very apt to write these types of programs. Having such an interpreter speeds up application development because many complex tasks can be bundled in one System instruction. The interpreter is easy to maintain because the program that  
5 drives the execution of the high level instructions, uses a rule base to "decode" them. To add high level instructions, only add rules are needed. These rules can be maintained independently of each other.

#### 10 High level display items

MotifShell also defines very high level "widgets" such as the logicBox. The logicBox is a widget that maintains two representations of the data it handles: a textual representation used to visualize the data and a  
15 logical representation that is used internally and has a richer structure than pure text. The application programmer can use and manipulate both representations. The synchronization of both representations and the mapping of high level logicBox instructions onto the lower level  
20 widget instructions of X-windows is done in a generic way. The logicBox defines a set of rules that the programmer should supply to handle all application-specific tasks.

The logicBox can be used to browse a graph. This is frequently used in the clinical workstation. Often the  
25 system has to present the user a set of options. When the user selects an option, a set of sub-options is presented. Selecting a sub-option might again list new options until the desired option is reached. This technique is used whenever the users needs to select from a list of options  
30 that is too big to show on one screen. E.g. there are over 700 Radiological examinations that can be requested. A graph structure is defined on top of this set that allows

to "zoom" in on the examination wanted. Often such large sets of options need to be browsed by the users. The logicBox allows to specify only the variable parts in the form of rules. The structure of the graph (i.e. the relation between the options: the layers on top of other layers of options, and the possible paths to navigate through this structure) are specified using Prolog rules. The program code that navigates through the structure, updates screens, reacts to events, etc. is all generic code. It interprets the rules that were specified to decide on the appropriate actions.

Another high level object is a table with the possibility to create graphs based on the data in the table. The table widget is used to display all kinds of lists in a tabular format. MotifShell provides several optimized predicates to access the table, sort, read out rows and columns, etc. ... GraphTools is a module that given a table allows the user to create pie charts, curves, bar charts, ... based on the data in the table. A programmer's interface to graphTools exists to make application specific charts in one command.

### Optimization

MotifShell also optimizes the speed of the interface. The creation of large and complex windows can require a few seconds. In the present System applications, the user often opens an electronic form just to look at the data content and then closes it again. To avoid creating the window each time it is opened, motifShell does not destroy the window when the user closes it but hides it. When the users wants to open the window again, motifShell makes the old window visible again. The programmer can



specify which parts of the window need to be re-initialized when a window is re-opened this way. This considerably speeds up the opening of windows. The performance penalty of the real creation is only incurred once for each window.

5 If a user wants a second version of the same type of window, motifShell detects this and creates a second copy. Upon closing this second copy is also not destroyed but hidden.

The trade-off is memory: because the windows are

10 not destroyed but hidden, the hidden representation still requires memory for storing it. MotifShell manages this memory usage and can decide to free up memory (by destroying a window) when needed. All this is completely transparent to the user: there is no difference between a

15 newly created and a "recycled" window. The users will only incur the performance penalty related to the first-time creation of the windows, at the beginning of a newly started session with the clinical workstation. After all windows are created once (or more if the user wants more

20 than one copy of a window simultaneously open) the system will be able to use almost only recycled windows. Most users will only open a subset of all the windows available in the clinical workstation because of locality of function. Due to locality of function, it is needed to

25 store the hidden representation of only a subset to have all windows recycled for a specific user.

While it is often more complex to optimize on a generic level, the pay-off is greater: all applications benefit from the optimization. The overall optimization is

30 usually better since not all programmers will do the effort to optimize each and every program.

## MESSAGETOOLS

MessageTools is the lowest module on the database side of System and the only module which directly uses the Sybase client. MessageTools has roughly three purposes:

- 5 - implementing generic support for the conceptual data model of the generator,
- provide a higher level interface to Sybase than the Prolog - Sybase interface by BIM, and
- optimization.

10

Generic support for the conceptual data model of the generator

The conceptual data model of the generator is based on a deletionless model. When the user inserts a  
15 message ("sends"), the system time-stamps it and stores the name of the user with the message. A user can delete ("omit") a message but the message is only removed from the view on top of the x#table by setting the omit flag to "o". When a user changes the data content of a message and sends  
20 this new content as a correction of the old message to the database, messageTools translates this operation into an omit of the old message, an insert of the new message and links the new message to the old one. To do this messageTools has program code that handles all messages in  
25 a generic way. It also uses specific SQL program code that was generated by formBuilder to handle those tasks that are too specific or would be inefficient to handle generically.

MessageTools works on the conceptual data model of the generator. All manipulations of the physical level  
30 of the data model are done using triggers or procedures. Most of this SQL program code is generated automatically by formBuilder.

### High level interface to Sybase

The application programmer only calls one Prolog predicate to do an insert, omit or delete. MessageTools will query the Sybase data dictionary to retrieve the necessary information to generate SQL instructions required to perform the database operation. One call to messageTools usually results in several Sybase client calls. Because it will itself query the data dictionary it is not necessary to add a patient messageTools each time a new table is created in the system.

MessageTools is the only module that directly accesses the Sybase client software. The advantage of this approach is that all higher level modules are shielded from the idiosyncrasies of the Sybase client. Apart from making the access to Sybase simpler, this is also a maintenance advantage. Changes in the Sybase client software cause changes in one module only. Usually software changes gradually but sometimes total revolutions need to be taken care of. Sybase chose in '93 to change its client software: the current client software (DB-lib) is still maintained and supported but no new features are added to it. The new interface software (CT-lib) will gradually replace the old and it is expected that support for the old interface will be dropped somewhere in the future. MessageTools will be ported from DB-lib to CT-lib and if the changes to messageTools only can be contained, no application program will need to be adapted.

### Optimization

MessageTools also optimizes Sybase access. Locality of function has as effect on the database that not all users will access all tables or views. MessageTools

remembers the meta-data it retrieved locally. If a user needs the data again later in the session, messageTools retrieves it from its internal data dictionary without going to the Sybase server.

5           Each user needs a "process" on the database server. The client passes SQL commands to this process which executes them and sends results back to the client. Opening a process each time an SQL command needs to be processed is too much overhead, and keeping unused  
10 processes open is inefficient. MessageTools manages process use. The application programmer specifies how many processes a user can keep open simultaneously. MessageTools will allow the opening of extra processes but will close all superfluous processes after they completed their work. All  
15 this is transparent to the application.

#### FORMTOOLS

FormTools implements the basic System 9 metaphor: the electronic mailing of forms. It uses motifShell for the  
20 user interface and messageTools to access the database. FormTools accesses these modules via the same API (Application Programmer's Interface) as the System 9 applications do. In other words, formTools is an application to messageTools and motifShell.

25           FormTools makes the connection between the visual representation of the message (the electronic form) and the database table used to store the message data. It handles all standard operations on forms in a generic way, again reducing the amount of code to be written. These standard  
30 operations can be invoked from the icon bar that resides on each System form. Their functions are briefly explained :

**Send** FormTools checks the form procedures (see next section), sends the content of the form to messageTools which sends it further on to the database. The content of the form is stored in a table with the same name  
5 as the form. Only the content of the fields on the form with a name that is also a name of a column in that table are stored. Only the minimal data needed to reconstruct the form will be stored. These are said to be part of the message. The user does not need to specify which widgets  
10 are part of the message: FormTools accesses the Sybase data dictionary to retrieve the name of the columns and automatically builds the message from the content of the corresponding fields. .

If the message is accepted by the database  
15 (database triggers perform checks on the content and may cause the insertion to abort), it is assigned a unique key (the dkey). The dkey and the name of the user who sent the form are displayed in the right hand corner of the form.

**Receive** FormTools will retrieve the content of all  
20 non-empty editable fields of the form. The resulting 'selection record' will be used to generate an SQL query to retrieve all records having the same values for these columns. The result is presented as a list of records.

**Clear** All fields of the form are cleared, that is,  
25 edit fields are emptied and check boxes are unchecked. Popup menus are reset.

**Initialize** The form disappears and a new copy of the original form template is drawn on the screen. If an initialization function is associated to the form, this  
30 will be used to regenerate the form.

**Context** Displays who sent the form and when.

Omit            The form is omitted (logically deleted: it is no longer visible in the table-view but still exists on the physical level).

Correct        After changing the content of the form the user can press this button to replace the old message with the new. What happens at the formTools level is highly similar to sending a form except that the dkey of the message to be corrected is passed along with the message to messageTools.

10

#### Form procedures, initialization and receive rules

If a form is defined correctly, System allows the user to add, omit and correct data without having an application program written for this. Sometimes the application needs to check the integrity of the data before allowing to store it or after storing data, the application might want to change something in another table or on the user's screen. This cannot be handled generically. To allow the application to interfere if necessary, form procedures can be defined by the application.

Form procedures are Prolog rules that will be called by formTools before and after each send, omit and correct. E.g. there are four types of that can be associated with the sending of a form: beforeSend, beforeSendOnly, afterSend and afterSendOnly. Since a correction is translated into an omission and a send, the beforeSend and afterSend are also called when a message is send to correct another message. Using these rules, application specific code can be executed between the generic parts. The before-rules are typically used to do checks on data integrity that are too difficult to express in SQL. The after-rules usually perform clean-up tasks

(e.g. closing a window automatically if the form was sent successfully). Many rules of the same or different types can be defined for the same form.

The initialization rules define what needs to be done when a form is opened. Usually these rules pre-fill the form with defaults (these may vary depending on the user, department, ...).

The receive rule can be used to intercept the normal way of doing a receive on a form. This is used if the generic implementation of the receive would be too inefficient. The receive rule can deduct more efficient queries based on application knowledge by looking at the parameters that are constraining the search.

#### 15 Storing only what is needed

When discussing the sending of the form, it has been stated that formTools only stores the content of the fields on the form that have a name that also appears as column name in the corresponding table. Usually there are many more fields on a form than the ones that are stored. E.g. many forms display the patient's name and number, but only the number is stored. This is common practice in designing a data model. The number is used as a reference to more data (in this case demographic data) so that if any of these change, the data need to be updated in only one place (the patient identification table). All other tables refer to the patient using the unique patient number and can retrieve the correct information from this table. If the data were duplicated in every table, the correction of a simple spelling error in the patient's name would require updates in numerous tables.

Such a situation usually occurs many times on even simple electronic forms. The assignment form e.g. assigns a patient visit (e.g. an ambulatory care visit) to an assistant and a supervisor. The form (see Figure 15) lists the name (first and last) of the patient, the number and type of the visit, and the ID , first and last name of the assistant and supervisor. Although all this information is necessary to allow the users to understand the form, only the visit number, the identification number of the assistant and the identification number of the supervisor are needed to express the relation between the patient's visit and the two physicians. The visit number is linked to the patient number via a reception table. The name of the patient can be retrieved from the patient identification table. Thus, only the three identification numbers are needed. If the form is to be understood by the users, the information linked to the numbers is to be displayed also.

Because this occurs many times on all forms, a generic solution was opted for. Just as formTools uses the table-view definition (which defines the conceptual level on top of the physical level) to insert data, it looks for the receive view to display the form. The receive view has the same name as the table-view with r# in front of it. The receive view ties the information from the different underlying tables together. FormTools uses it to display data on the form. Just as with sending, column names in the view definition correspond to fields on the form.

In a way the receive view definition acts as an application specific rule which is used by a generic application (formTools). It would be possible to specify the receive view in Prolog, but this would be much less efficient. Because it is specified as an database view, the



receive view can also be used to create new views.

### High level interface

Apart from being a generic application in its own  
5 right, formTools provides also a high level interface on  
top of both messageTools (Sybase) and motifShell  
(Motif/X-windows) to build specific applications with.  
Theoretically one could make any application just using  
formTools' functionality but this would not be  
10 ergonomically acceptable. Users want and need  
application-specific short cuts. This results in extra  
buttons and menus on the forms. FormTools provides  
predicates to manipulate forms that ease the implementation  
of such extra functions.

15 Users view the contents of other forms usually in  
the form of (work)lists. A typical user permanently  
switches between querying the database and adding data. The  
handleQuery predicate allows to specify a query and the  
options to display the results; it sends the query to the  
20 database, retrieves the results and displays them. Since  
there are many parameters that can be specified, a small  
interpreter was written to generate the low level program  
code that corresponds to each of these parameters. There is  
of course an overhead in creating a predicate of the  
25 complexity of handleQuery but it pays off: almost all lists  
in System 9 programs are generated using this predicate.

### Conclusion

The goal of the present System generator is to  
30 handle as much processing as possible on a generic level.  
This reduces the total amount of program code and thus  
increases maintainability not only through code reduction

but also through standardization. The richness of the tools allows faster development. The drawback is that the tools have to be built and maintained themselves. The larger the system, the larger the pay-back of such an approach since  
5 more people and more program code benefit from the same set of tools.

The present System generator is and has been constantly improved. Each repetitive programming task is scrutinized to see if it can be split in a generic and an  
10 application specific part. If so, and if it is expected to need the generic part in the future, the generic functionality is added to the appropriate module or a specific module is created. This way, the generator is constantly refined. Jean et al. advocate the use of a  
15 homogeneous platform to integrate all modules of a clinical workstation. The authors discern 4 aspects of integration: data, presentation, communication and control integration. The System generator tackles the first two of these by providing development tools. Control integration is partly  
20 modeled by the data modelling strategy (progress along the time-line of the unit of work; non-conceptual tables to explicitly store the state of this progress) but no generic software modules are provided to aid this. A generic communication module that operates on the content level of  
25 the communication stream is not yet developed. Such a module will probably be built using the Health Level Seven (HL7) communication protocol.

#### Development tools

30 To automate and speed up the development process, several development tools have been developed. One (BX) was bought. Their use in the development process is shown in

Figure 16.

### Builder Xcessory

Builder Xcessory or BX is a graphical user  
5 interface design tool from ICS. With BX the programmer can  
"paint" a window. The programmer begins by drawing the  
rectangle of the top level window. All available widgets or  
display items can be chosen from a palette and put within  
this window. The relations between the display items (e.g.  
10 the alignment, size, shape,...) can also be set here. After  
specifying the visual aspect of the window. BX can generate  
the creation function for this window in the programming  
language C.

The application programmer does not change this  
15 creation function. It is linked to a Prolog predicate so  
that it can be called from the System applications.

### FormBuilder

FormBuilder was developed to automate the  
20 generation of the database objects associated with  
electronic forms. After painting the form using BX and  
generating the creation function, the programmer uses  
formBuilder to generate SQL. FormBuilder creates the form  
using the creation function. The user then specifies the  
25 fields to be stored in the database by clicking on them.  
Then the types (integer, character, real, ...) can be  
specified. Eventually the SQL to create the table, the  
table-view and the generic parts of the triggers to support  
the integrity of the physical level of the data model, are  
30 generated. FormBuilder generates the SQL code and presents  
it in SQL windows of dbDashboard where the programmer can  
add the application specific parts. FormBuilder is a rule

based system that contains rules for each of the SQL parts to be generated.

#### DBDASHBOARD

5                   Because only the standard part of the SQL can be generated and stored procedures and triggers need to be maintained, a tool was developed, that facilitates creating and editing database objects and that is integrated in the System environment. DbDashboard provides a window from  
10 which SQL can directly be sent to the database. Options to generate time and input/output statistics and to have the optimizer print out the query plan can be set from this window. DbDashboard provides (amongst others) menu options to create and maintain tables, views and procedures, add  
15 comments to them. It creates SQL code to set permissions and can be used to check differences between databases (e.g. test and production databases can be compared).

                  DbDashboard is available to developers only. It is intended to add tools to migrate tables, views and  
20 procedures from the test to the production database.

#### MAURICE

                  To automate part of the debugging process a program checker called Maurice has been developed. It is a  
25 Prolog program that can read another Prolog program and try to detect bugs. It consists of three parts: the inference engine, the standard Maurice rules and the specific Maurice rules. The inference engine reads the code and applies the standard Maurice rules to it. Standard Maurice rules may  
30 invoke specific Maurice rules.

                  Standard Maurice rules check for suspicious code. E.g. typing errors in variable names are a common cause of

bugs. Maurice will check for variables that appear only once in a predicate and report them. Usually a variable will appear more than once in a predicate: the first time to instantiate it (give it a value) and further on to do something with that value. A variable that just "sits" there is suspicious and is reported, e.g. if Maurice reports that it found two "lone variables" called `_myVariable` and `_myVariable` the programmer will immediately know that he made a typing error. Program code that calls a predicate that does not exist is also suspicious: probably it is a (typing) error since it makes no sense to try to use something that does not exist.

Maurice also logs into the database as a user. If it detects that the program will try to use a database object (most often a procedure) it will check if this procedure exists in the database. For each of the System modules of the generator a corresponding Maurice rule base exists to check for the correct usage of the programmer's interface it defines. E.g. if the program tries to set the value of the field A on the form B, Maurice will check if the form definition for form B exists and if it contains a field definition for field A.

### Tools

The following modules are sets of tools that are very general in nature. They were developed to be used in several System applications.

### S9SERVICES

This module was developed to hold medical building blocks that are needed in most applications but that are not general enough to be implemented in the

generator. Examples of such building blocks are: tools to store patient information within an application, graphMaker (i.e. a tool to create and browse a graph of options), explicit access control checks, smartAsk (functions to automatically and intelligently generate windows to request data from the user), ...

#### TEXT ASSISTANCE

Many acts in the hospital end with one physician writing a report to another. Some of these can be standardized. These reports can be generated by asking the clinician to specify the relevant parameters and then generate text based on the value of these parameters. This has two advantages: by having the computer ask for the parameters, the reports become more standardized and no parameters can be forgotten (there is no difference between paper or computerized structured reports. The second advantage is that it takes much less time to generate such a report.

To facilitate the programming of text generating procedures, a specific language has been developed. The language looks more like a conventional programming language and has a syntax totally different from Prolog. These text generating programs were compiled into Prolog data structures. Text assistance provides an interpreter that generates a report, given a set of parameters, their values and a compiled text assistance program.

#### UZ PrologTools

UZPrologTools is a module which was developed to function on the lowest level (i.e. it does not use any other module) but is itself used by almost any module in

the system. It contains a set of small but handy predicates to facilitate programming. E.g. a set of predicates to read and write records of fixed length, a debugging tool, list manipulation predicates, ....

5

Connection between the mainframe and the System environment

A fast bi-directional link is necessary between the administrative system on the mainframe and the System environment.

10

#### LINK BETWEEN THE MAINFRAME AND THE SYSTEM DATABASES

To insert and request data from a Sybase database, the choice was made for an interface that would allow a (COBOL) program to execute an arbitrary stored procedure in Sybase. The COBOL program that wants to communicate with the Sybase server, first sets up an LU 6.2 connection with an intermediary UNIX machine. LU 6.2 is a standard for peer-to-peer program communication. This is a direct communication between two programs running on (possibly different) computers. It sends a data string over this connection to a transfer program on the intermediary machine. This transfer program is equipped with the Sybase client software. It sends the string to the Sybase server which executes it. If the data string is a query, the transfer program retrieves the results and transfers them back to the requesting program on the mainframe.

#### LUTools

LUTools allows to set up a LU 6.2 connection from within a System application with the mainframe. LUTools provides a high level Prolog interface on top of the LU 6.2 libraries provided by the computer manufacturer. With

LUTools an arbitrary CICS18 transaction can be executed. The transaction can return data to the Prolog program. It is used to communicate with the mainframe system to retrieve e.g. laboratory test results or to insert data  
5 into the billing system.

#### Order entry in System: the service manager

The service manager uses a generic framework to handle services. It defines the generic storage structure  
10 of services, the operations that can be done on services (request, perform, annul and close) and the framework for the user interface. The framework is completed by user defined rules that allow to define the specific parts. An overview of the service manager framework will be now  
15 given.

#### STORAGE STRUCTURE FOR SERVICES

##### Problem

The data for such services is structured but  
20 since there are so many different acts that may be requested, the number of structures necessary to implement them all is huge. For this reason it is infeasible to store each type of structure in a separate file or database table. Most of these tables or files would be small and  
25 reintegrating data on screen from all these objects to give a global overview of a patient is too inefficient to achieve an acceptable response time.

The solution could be either to limit structure to some greatest common denominator or to make a very  
30 general structure that subsumes the specific ones. The second option was chosen. To do this some constraints of using a relational databases had to be solved. A relational



database is very strict in the storage structures it allows: the only structure allowed is the table. The columns of the table are fixed in number and type and need to be predefined. Altering the structure of a table usually means stopping the programs that use it, change the table definition, install programs adapted to the new structure and restart them. This is cumbersome and cannot be done each time a new act needs to be defined.

- 10 Solution: translate generalized table structure to specific logic terms

To store the acts generalized tables were used. These tables can accommodate the storage of any service. There are four basic tables that the service manager employs: request, perform, annul and close. A service can be directly performed without it being requested or it can be requested and then performed or annulled (both close the request). Some requests are continuous requests, these are requests that stay open even if the service is performed (e.g. for requests that have to be performed several times). Continuous requests have to be closed explicitly. (For simplification, only the request and perform tables will be used to discuss the underlying principles of the service manager).

25 Services are grouped in types. A service type collects all services that logically belong together. E.g. there is a separate service type for the radiology request/perform system and another for general medical activities. For each of these types a separate set of these four base tables exist.

30 The service manager tables constitute of three parts: the standard, fixed and variable part. The standard

part defines the columns that are the same for all service types but differ between request and perform. The fixed part defines the columns that are fixed for a certain service type. The variable part is where the flexibility of the service manager lies. The variable part is a set of columns of different data types and different lengths. The columns that can hold an integer number are called int1, int2, ... ; the columns that can be used to store a bit value bit1, bit2, ... etc.

While the columns of the standard and fixed parts have one interpretation for all rows in the table, the columns of the variable part have an interpretation depending on the service stored in the row. Each service can have some attributes that need to be stored (e.g. a number, the name of a medication, type and number of materials used, ...). These parameters are mapped on the physical columns of the variable part. So the column called int1 can hold the number of incisions that were used for a certain type of surgery but in another service it can hold the number of catheters used. The logical structure of a service is thus mapped onto the generic table structure.

The service manager operates on the generic level of the four base tables. It uses user defined rules to access the specific tables used to store the service requests and performs of a given type. Several types can use the same set of tables but one type must be stored in one set of tables. The translation between the storage structure and the logical structure of the service is also done by rules. As soon as a service is retrieved from the database it is translated to its logical structure. Before storing a service request or perform in the database the logical structure is again translated to the structure of

the table. Translation rules can be defined for a whole type or for a specific service.

#### Auxiliary tool: service type maker

5           The structures needed to define the mapping between the logical and the physical representations are quite large and thus error-prone. To aid in the construction of these structures a program was written that allows to define parameters for a service and specify the  
10 physical storage type. The service type maker then deducts the optimal mapping structure for this service and generates the Prolog code for it.

#### USER INTERFACE

15           A generic user interface was also constructed. The basic structure of the interface consists of a selector, an editor and a collector. Consider requesting a service (to perform services is highly similar). The selector is used to select a service request. When a  
20 service request is selected its parameters can be edited in the editor. A default editor is supplied, but for those services that have extra parameters, the service manager will either construct a window to request values for these parameters or the application can define a special editor  
25 that will be used by the service manager. After editing, the service request can be sent to the database. The collector then shows all services requested for a patient. Since there are many different types of services (each with their own set of parameters) that all need to be shown in  
30 one collector, only a textual representation of the services can be displayed. A rule base is used to transform the logic term representation of the service to a textual

representation which is shown in the collector.

The service manager combines functionality of many other modules already discussed earlier :

- service requests and performs can be sent, corrected or  
5 omitted. They are implemented as System messages;
- the service manager calls equivalents of the form  
procedures before and after each database operation.  
Using access predicates defined by the service manager  
the user can access the logic representation of the  
10 service objects;
- the selector and collector use the logicBox. The selector  
often uses the logicBox to navigate through a graph (see  
figure 14).

The selector interacts with the editor and the  
15 collector via the standard selector protocol. This allows  
to create specific selectors if need be. The selector is  
subject to much ergonomic constraints. The ideal selector  
is one that guesses the next service to be requested. To  
allow fast selection of the most common services specific  
20 graphs for each department or ward are created. E.g. the  
Radiology request graph starts with the top 20 most  
requested Radiological examinations for each department.

Apart from browsing the graph of services, the  
user can also type in part of the description of the  
25 service and then search the database for matching services.  
Once the users are familiar with working with the keyboard  
this is often the fastest method of retrieving an option  
from a very long list. Teich et al. take this even a step  
further. Next to selecting from a hierarchical options  
30 list, they implemented a sort of command line interface  
where partial orders can be typed in. Upon pressing "enter"  
the system searches for matches and tries to expand the

order(s). This allows not only to type in more orders in one batch but also to type in the parameters directly as well.

To speed up selection of the most common activities the grid was added. The grid is a rectangular matrix with 54 cells containing abbreviations of the 54 most common services for a particular ward. When opening a service manager window, the system tries to guess the probable location of the patient. This ward number is used to find the appropriate rule to fill the grid. The cells in the grid act as buttons: clicking a cell moves that service to the editor. The grid gives additional one-mouse-click-access to 56 services. Because the grid adheres to the standard selector protocol, the editor and collector did not need to be adapted when the grid was added.

One of the main problems in creating a user interface is the difference between first-time or occasional users and experienced or power users. The first category requires a verbose interface and navigating through a graph or a hierarchical set of options allows them to contemplate every step. The novice or occasional user is confused by too many shortcuts and cannot memorize them since he does not use the system often enough.

The experienced user knows exactly what he wants and where it is located in the system and will always require a larger set of shortcuts that brings him with as few mouse-clicks as possible to the location he wants. In the grid all options are in a fixed location. Experienced users can select an option motorically without reading the contents of the cells.

## The clinical workstation

### Introduction

Active participation of clinicians in the specification:  
the sounding board group

5           The Surgical Pathology and Radiology systems were developed by discussing the specifications with key clinical users of the departments. Not only functional specifications were discussed but also the underlying data model. The use of the message modelling concepts  
10 facilitated this approach.

          The hospital management selected four clinical specialists from different disciplines and one nurse to serve as a sounding board to the developers. All members were of senior rank and had extensive experience in a  
15 clinical setting. After 9 months the head of the administrative department and the head of the pharmacy joined the group.

          The group met with the development team for almost a year every week during a 2 hour meeting. All  
20 design decisions were presented to this group. Later in the development prototypes were used to advance the discussion.

### One medical file, one set of procedures

          Central to the design of the clinical workstation  
25 is the idea of an integrated medical file. Not only would the data be contained in one database, the functionality would be identical on all wards. Being a teaching hospital, many of the physicians have change departments frequently. If the functionality would differ too much this would  
30 present a training problem.

          One of the main tasks of the sounding board group was to warrant that the functionality was kept sufficiently

general to implement on all wards. They spotted where customization would be required. Automating an organization changes the workflow and thus procedures must be adapted. The sounding board group also defined the procedures that  
5 all departments must use when working with the clinical workstation.

#### Software modules of the clinical workstation

The clinical workstation currently consists of 8  
10 modules. All but two (registration of vital and physical parameters and medication prescription) are in production.

To the user all these modules are integrated via the dashboard.

The dashboard in the clinical workstation  
15 consists of two parts: a patient linked part and a contact linked part. Figure --- shows the dashboard and explains the function of the buttons. The dashboard is a navigation instrument: the buttons activate a module of the clinical workstation. Most forms have a dashboard icon on them.  
20 Clicking this icon retrieves the relevant dashboard. The dashboard takes the user to the forms and vice versa.

#### The contact module

The contact module is the main module of the  
25 clinical workstation. A contact can be an outpatient visit, a hospitalization, a gastroscopy, an operation, a stay in intensive care, a chemotherapy treatment,... All patient contacts are monitored using this module. A contact differs from patient admissions (or transfers) in the sense that  
30 one contact can have many admissions (e.g. a renal dialysis treatment will have an admission each time the patient is dialyzed). On the other hand, one admission can have

several (simultaneous) contacts. E.g. a surgical patient will have an open contact for the surgery department and may have a separate one for the operation itself. A stay in the ICU might also cause another contact to be opened by  
5 the physicians of the ICU. A contact is a medically logical unit, as opposed to a patient movement (admission, discharge or transfer) which is a movement in time and space. When the patient is discharged the contact will usually not be closed. The contact is closed when the unit  
10 of work is completed.

A contact has several phases, some of which are optional. The phases of the contact make up a unit of work. Each of the phases are represented by an electronic form (for an example of the assignment form. The contact starts  
15 with a reception form. This links the contact to a patient, and a department (e.g. pediatric Nefrology). The type (inpatient, outpatient, ...) is also determined here. The second phase, assignment, assigns the contact to a physician and a supervising physician or supervisor. The  
20 unit of work needs to be completed either by the validation of an medical report or by the explicit statement that no report was necessary for this contact.

The data captured by the contact module governs most of the workflow for the physicians. Especially the  
25 first two phases capture the information necessary to steer the workflow. The reception form gives the data to divide the work among the physicians of a (sub)department using the assignment form. These data are subsequently used to make worklists for individual physicians (such as a list of  
30 reports that need to be written or, for a supervisor, the list of reports that are ready to be validated).



The most important piece of data captured in the contact module is the medical report. One of the main products of a hospital is information (to the patient, the treating physician,...) and most of this information is  
5 under the form of a medical report from one physician to another. In a teaching hospital, many reports are written or dictated by physicians in training. These reports need to be validated by a supervisor. An unvalidated report can be printed but "unvalidated" will be printed obliquely over  
10 it so that it is easy recognizable. After validation the reports can be printed. Subsequently they are signed and mailed to the (external) physician who referred the patient.

#### 15 Optional phases or forms

Several other forms are linked to a contact but are optional. The note allows to attach a small note to the contact (akin to post-it notes). Intermediary reports allow to report progress without closing the contact. This is  
20 used for long term contacts: a renal dialysis or chemotherapy episode is usually represented as one contact. The VINO (Verpleegkundige Informatie Nota bij Ontslag - Nursing Information Note at Dismissal) is used to give information to the patient concerning medication, personal  
25 care, ...

#### Organizational problem caused by automation

Before the automation, reports were typed out centrally by typing clerks or by secretaries of the  
30 department. The letter to be signed stayed with the paper file, was signed and returned with the paper file for further handling. The report and the paper file usually

travelled together.

With the clinical workstation, validation is done on screen, and can be done on any terminal in the hospital. This causes work to be shifted from the secretaries to the supervisors. A supervisor can validate a report without the paper file since most of the data are available on-line; he does not need to wait for the paper copy. As soon as a report is written, it appears on the validation list of the supervisor. When the report is validated, it is automatically printed in several copies (one for the referring physician, one for the medical file, a personal copy, ...). The problem is that the supervisor ends up handling the physical copies of the report and is responsible that they reach their destination.

This was solved by using "electronic signing". The problems arise where the flow of the report changes from electronic to paper. This has to be at the validation phase when a written signature is needed. An addition was made to the contact module to dissociate validation from printing and signing. When the report is validated, it moves to a print list. The secretaries are responsible for handling the print list. Either the reports are signed in batch at the secretary's office or better still, the physical signature is replaced by a notice at the end of the report stating "this report was electronically signed by dr. xyz at date dd.mm.yy".

#### Migration problem: historical data

Another encountered problem was one of migration. Most of the departments already used computers to type the medical reports. Different departments had different computer systems. A possibility to overcome this major

problem, could be the creation of a historical database, load all data and link the historical database to the clinical workstation. Different source systems would result in different historical databases and the user would see a  
5 difference between data from the historical system and data from the new system.

Instead a load program was developed to read in the historical data and to translate the historic data model to the data model used in the corresponding  
10 application. The load program uses a rule base to make an educated guess for the missing data. If information cannot be deduced or guessed at all, sensible but recognizable defaults are entered. This technique was applied for the first time in Radiology. 244.451 radiological reports could  
15 be retrieved this way. It was repeated for Pediatrics (94.866 reports), Oncology (26.727 reports), Gynecology/Obstetrics (96.518 reports) and Hematology (45.266 reports).

The main advantage is that it populates the  
20 system with data as if the department has been working with it all along. There is no difference in structure between historical data and new data, but certain data items might be missing or set to defaults. No extra software needs to be written to create and integrate the historical database  
25 with the System applications.

The disadvantage is that disk space is wasted on storing millions of default values that were generated by a computer and thus carry no informational value. At current disk prices this cost is easily offset by the cost of  
30 developing specific software for a historical database. The other disadvantage is that the load program is more complex since it must translate one data model into another and

generate or deduce data were needed. This has to be repeated for every type of load but this is a one-time effort and some of the software can be reused by using again the technique of inference engine and rule base.

5

#### Appointment system: slot manager

The appointment system is called the "slot manager". The appointment books for scheduling outpatient visits consist of many empty slots. The number of slots per  
10 resource and per day is limited and predetermined. The slot manager manages the electronic equivalent of these paper books. It uses a gigantic grid of slots: the X-axis is the (start) time and the Y-axis the resource (a physician, but it can also be an operating theater, a procedure, ...).  
15 Each slot also has a duration associated with it. If a patient number is stored at the intersection of time T and resource A, this means that resource is allocated to that patient for the duration associated with the slot.

The advantages of the slot concept are that very  
20 little checking needs to be done at the time of booking: if the slot exists and it is empty it can be booked. It is not necessary to check for double bookings or if the resource will be available at all. All this is verified once when the electronic appointment books are created. Searching for  
25 the free slots for a resource (e.g. when a patient wants to see a particular physician) is done by accessing the matrix of slots via the Y-axis. The disadvantage of this approach is that all slots need to be predefined long beforehand (at least a year; for oncology two years), and this takes up  
30 space. It also requires the physicians to decide long beforehand when and how long they allow appointments to be booked.

An alternative approach to build an appointment system is to have one large free space of time and resources and check, at the time of booking, if the resource is available. Instead of explicitly stating which slots are available, there are rules that define what is allowed and what is not. Slots not yet occupied do not take up space but the booking becomes much more time consuming because these rules need to be checked for each booking. E.g. if patient A wants to see physician B Tuesday at 10:00 h, the system needs to check if B is available for outpatients at that point in time, and is not yet booked for another patient in an overlapping time frame. The system also needs to check if the maximum number of patients for that day for Dr. B is not yet reached (to avoid overbooking). Searching for any physician from the department of pediatrics that is available for an outpatient visit is much more time consuming.

Because the booking process (finding a free slot and placing a patient in it) needs to be fast (usually somebody is waiting for an answer) the first design was used. Free slots are searched using a query screen where several search criteria can be entered (see Figure 6-5). The free slots qualifying the search criteria are listed and selecting one of these puts the patient in the slot. The system discerns between book owners and other users. Normally users can only see free slots and never get a list of all patients booked for a particular day or physician for reasons of privacy. They also cannot overbook. A book owner both can overbook (i.e. create duplicate slots) and see the list of patients that are booked in the electronic books he owns. Book owners can tie information to slots (e.g. "no new patients; only for follow-up"). The booker of

the slot can add information about the patient to the slot.

The advantages of electronic appointment books are :

- patients are always identified correctly and readably;
- 5 - the appointment data are transferred electronically to the medical archive to retrieve the paper files. They are also loaded in the administrative system so that when the patient is admitted the correct data can be pre-entered and the admitting process is sped up;
- 10 - appointment books are accessible from any point in the hospital instead of only at the appointment desk;
- it is possible to give an overview of all appointments for a patient.

#### 15 Auxiliary tool: slot maker

Because slots constantly need to be added a slot maker program was written. This program takes a pattern of slots for a book (e.g. every Monday, Friday at 9:00, 9:15, 9:30, 10:00, 10:30, ...) and generates the rows in the  
20 table that represent the slots. This is again a rule driven program.

#### Conflict with deletionless-ness of System data model

The slot manager needs all slots to be ready-made  
25 before they can be booked. The users update them. This is not an additive data model and implementing it as one would be senseless: the first sender of the slots would always be a program (the slotmaker) and all real operations would be corrections. Because the log of all operations on the  
30 appointment books (which is an implicit advantage of using a deletionless data model) is not wanted to be lost, all changes to the appointments are logged in a separate table

using Sybase triggers.

#### Service manager

A lot of the communication in a hospital between  
5 care providers is requesting and reporting some sort of act  
that is (to be) performed on a patient. Order entry for  
Radiology or laboratory tests, requesting nursing act,  
gastroscopy, ECG requests, ... are all examples. This is  
often called act management and some projects intend to  
10 define a generic framework for it.

Order entry is a part of act or service  
management. As early as 1970, Maurice Collen advocated that  
"physicians should enter their medical order directly into  
the computer" for reasons of accuracy and completeness.  
15 Many order entry systems fail(ed) but in the early 90's  
there was a renewed emphasis on physician order entry owing  
to several important factors :

- the advances in computer technology thus allowing better  
user interfaces;
  - 20 - an increase in computer literacy with health care  
providers of all levels; and
  - the interest to develop a complete computer-based patient  
record to increase the quality of care.
- 25 Advantages of physician order entry are manifold :
- all orders are legible and complete (the software can  
block a request until all mandatory fields are completed  
but this is no guarantee that the data entered make  
sense);
  - 30 - orders reach the service department immediately;
  - orders cannot be lost and pending orders can be reviewed.

Table 1 : Tables partaking in the example query

Table	Function
patienten	Demographic data for all known patients.
x#receptie	Attributes a contact number to each unit of work and links it to a patient; all subsequent phases pertaining to that contact share the same number.
x#artsSup	Relation between contact number and ID of assistant and supervisor
x#verslag	Contains all reports. A contact can have several intermediate reports but only one final report (designated by the report type "eindverslag"). Each report has a report number. This table links report numbers to contacts.
x#validatie	Contains the report number, contact number and the ID of the supervisor who validated the report.
x#S9User	Contains descriptive information (name, department, telephone, ...) on all users of the system.



*Table 2 : Order of table accesses in query 1*

x#verslag	Table Scan (to create worktable)
x#verslag	Table Scan (group by)
x#validatie	Index : verslagNr (to create worktable)
Worktable	Table Scan
x#verslag	Index : verslagNr
x#artsSup	Using Clustered Index
x#receptie	Using Clustered Index
allePatienten	Using Clustered Index
x#S9User	Using Clustered Index

TABLE 3.

## 1 Query plan for query 1

## STEP 1

The type of query is SELECT (into a worktable).

GROUP BY

FROM TABLE

x#verslag

Nested iteration

Table Scan

TO TABLE

Worktable

## STEP 2

The type of query is SELECT (into a worktable).

GROUP BY

Vector Aggregate

FROM TABLE

x#verslag

Nested iteration

Table Scan

FROM TABLE

x#validatie

Nested iteration

Index : verslagNr

TO TABLE

Worktable

## STEP 3

The type of query is SELECT.

FROM TABLE

Worktable

Nested iteration

Table Scan

FROM TABLE

x#verslag

Nested iteration

Index : verslagNr

FROM TABLE

x#artsSup  
Nested iteration  
Using Clustered Index  
FROM TABLE  
x#receptie  
Nested iteration  
Using Clustered Index  
FROM TABLE  
allePatienten  
Nested iteration  
Using Clustered Index  
FROM TABLE  
x#S9User  
Nested iteration  
Using Clustered Index

## 11.2 Query plan for query 2

STEP 1  
The type of query is SELECT.  
FROM TABLE  
statusContact  
Nested iteration  
Index : usernameSup  
FROM TABLE  
x#S9User  
Nested iteration  
Using Clustered Index  
FROM TABLE  
x#verslag  
Nested iteration  
Using Clustered Index

## 11.3 Query plan for query 3

STEP 1  
The type of query is TABCREATE.  
STEP 2  
The type of query is INSERT.

The update mode is direct.

Worktable created for SELECT\_INT0.

FROM TABLE

x#artsSup

Nested iteration

Index : usernameSup

TO TABLE

Worktable

STEP 1

The type of query is DELETE.

The update mode is deferred.

FROM TABLE

#supervised

Nested iteration

Table Scan

FROM TABLE

x#verslag

Nested iteration

Using Clustered Index

FROM TABLE

x#validatie

Nested iteration

Index : verslagNr

TO TABLE

#supervised

STEP 1

The type of query is SELECT.

FROM TABLE

#supervised

Nested iteration

Table Scan

FROM TABLE

x#S9User

Nested iteration

Using Clustered Index

FROM TABLE

x#verslag

Nested iteration

Using Clustered Index  
FROM TABLE  
x#receptie  
Nested iteration  
Using Clustered Index  
FROM TABLE  
allePatienten  
Nested iteration  
Using Clustered Index

Table 4 . Performance results. For the three queries the number of table scans, CPU time and elapsed time are compared.

	Size (#rows)	Number of table scans		
		Query 1	Query 2	Query 3
x#receptie	132.043	6		6
x#artsSup	132.374	454	6	1
x#verslag	158.371	456		2.248
x#validatie	114.391	114.040		1.053
x#S9User	1.789	6	6	600
allePatienten	1.055.629	6		6
statusContact	7.772		1	
#validated				2
Timing				
Server CPU time (msec)		129.000	<100	1.700
Elapsed time (msec)		129.746	446	3.055
Ratio elapsed time		291	1	7

Table 5 : Disk overhead of the non-conceptual tables. The total size of the non-conceptual tables and of each database is shown. The overhead of the non-conceptual tables expressed as a percentage of total database size decreases with time.

	Surgical pathology	Radiology	Clinical workstation
Months operational (Aug. 95)	59	38	8
Non-conceptual tables (Mb)	1,2	4,49	15,08
Total DB size (Mb)	1641	4121	844
Overhead (%)	0,07%	0,11%	1,79%

*Table 6: Summary of effect of scaling up the number of users, size of the application or amount of data of a System 9 application on the presentation workstation, application server or database server.*

Hardware Application	Presentation workstation	Application server	Database server
Number of users	Trivial: one per user	N users per application server depending on the processing power and available memory	More processing power and memory needed
Size of the application	No influence	Increase the amount of virtual memory per user	No influence
Amount of data	No influence	No influence: only transient data are kept here	More disks needed



CLAIMS

1. A relational database compiled/stored on a computer environment and adapted for access by application programs executing a query within said database and  
5 compiled/stored on said computer environment comprising :  
- a first set of tables with first columns and tuples containing first data;  
- a second set of tables with second columns and tuples containing second data, each of said second data being a  
10 redundant representation of at least one of said first data.
2. The relational database as recited in claim 1, wherein said second data are a copy of a part of at least one of said first data.
- 15 3. The relational database as recited in claim 1, where said second data are derived from said first data by an adaptation of said first data.
4. The relational database as recited in claim 1, where said second data are derived from said first  
20 data by an operation on said first data.
5. The relational database as recited in claim 4, where said operation is a multiplication.
6. The relational database as recited in claim 4, where said operation is a division.
- 25 7. The relational database as recited in any one of the preceding claims, wherein said second data support said query within said first data whereby the performance of said query within said first data is increased.
- 30 8. The relational database as recited in any one of the preceding claims, where said application programs are compiled/stored on said computer environment.

9. The relational database as recited in claim 8, further comprising programs being executed while data is added to a table of said first set of tables whereby said programs generate said second data of said  
5 second set of tables.

10. The relational database as recited in any one of the preceding claims, wherein the said first set of tables consists of a physical level, a conceptual level or an application level.

11. The relational database as recited in claim 10, wherein each of said first data are electronic messages, possibly representing the contents of electronic forms.

12. The relational database as recited in  
15 claim 11, wherein said messages represent essences consisting of the group of processes, operations, services, acts, objects and persons within a defined world.

13. The relational database as recited in claim 12, wherein said defined world is a hospital.

20 14. The relational database as recited in any one of the preceding claims, wherein one data is in one tuple, each of said first data being permanently stored in one tuple being added to a table of said first set of tables, whereby the database is deletionless and additive.

25 15. The relational database as recited in claim 14, wherein said tuples containing said first data are labeled according to the operation creating said first data, said operations selected from the following: inserting, omitting or correcting said first data.

30 16. The relational database as recited in claim 15, wherein said tuples containing first data are labeled according to a creator creating said first data, to

the date of the operation creating said first data and possibly to the link between the new version of said first data and the old version of said first data.

17. The relational database as in recited  
5 claim 11, wherein a set of messages are related as a unit.

18. The relational database as recited in claim 17, wherein said unit is represented by at least one tuple in said second set of tables, said tuple representing said unit within said second set of tables being deletable.

10 19. A method for executing queries within a relational database as recited in any one of the preceding claims, comprising the steps of :

- selecting tuples in said second set of tables, and
- reading out the tuples of said first set of tables  
15 corresponding to said selected tuples of said second tables.

20. A method for executing queries within the relational database as recited in claim 17 comprising the steps of :

- 20 - selecting tuples of said second set of tables corresponding to said unit; and
- reading out the attributes corresponding to one column and one tuple of said first set of tables corresponding to said selected tuples of said second tables  
25 corresponding to said unit.

21. A database access system compiled on a computer environment, comprising :

- a relational database including :
  - a first set of tables with first columns and tuples  
30 containing first data,

- a second set of tables with second columns and tuples containing second data, each of said second data being a redundant representation of at least one of said first data; said database being adapted for access by application programs executing a query in said database;

- meta-data; and

- means for optimizing the steps of accessing said database, said means comprising tools for retaining a set of meta-data after first data are inserted in said database, said set of meta-data verifying errors in an insertion of next first data in said database.

22. A system for developing software for an application to be compiled on a set of computers, said system comprising :

- a relational database with :

- a first set of tables with first columns and tuples containing first data, said first data being electronic messages, being the contents of electronic forms;

- a second set of tables with second columns and tuples containing second data, each of said second data representing at least one of said first data;

- first tools supporting a user interface;

- second tools accessing said database; and

- third tools implementing said electronic messages and linking said database with said user interface to thereby store said electronic messages as data in said database and whereby said electronic messages can be entered or accessed via said user interface.

23. The system as recited in claim 22, further comprising means for adding, omitting and

correcting said electronic messages.

24. The system as recited in claim 23, wherein said means include within a rulebase, first rules for checking data integrity before adding said data, second  
5 rules for executing the steps of omitting and adding data after corrected data are entered, and third rules for closing said user interface.

25. The system as recited in claim 24, wherein said electronic messages represent essences  
10 consisting of the group of processes, operations, services, acts, objects, and persons within a defined world.

26. The system as recited in claim 22, wherein said second tools comprise tools for entering said electronic messages in said database as tuples with columns  
15 in a specific table.

27. The system as recited in claim 22, wherein said relational database is a Sybase type of database, said user interface is a workstation or a terminal and said tools are developed in Prolog.

28. The system as recited in claim 22, further comprising modules being specific for one application according to one of said essences within said defined world.

29. The system as recited in claim 22, wherein a set of the first data being comprised in said  
25 database is displayed on said user interface.

30. The system as recited in claim 29, wherein said first tools comprise means for maintaining a subset of said set of first data on said user interface  
30 while storing said set of first data.

31. The system as recited in claim 30, wherein said set of first data is represented as a graph

with nodes representing parts of said set of first data and arcs representing the inter-relationships of said parts.

32. The system as recited in claim 31 further comprising means for browsing said graph.

5           33. The system as recited in claim 22 further comprising fourth tools for developing a specific application including means for generating database objects associated with said electronic forms.

10           34. A clinical workstation implementing on a computer environment a representation of a group of processes, operations, services, acts, objects and persons within a hospital comprising :

- a relational database having :

15           - a first set of tables with first columns and tuples containing first data, said first data being electronic messages being the contents of electronic forms wherein said first set of tables is organised as a set of generalized tables according to the different types of said operations;

20           - a second set of tables with second columns and tuples containing second data, each of said second data being a redundant representation of at least one of said first data;

25           - software modules, integrating a medically logical unit of said hospital.

- a user interface including a dashboard and integrating said modules; and

- a generator stored on said computer environment comprising :

30           - first tools supporting a user interface;  
- second tools accessing said database;

- third tools implementing said electronic messages and linking said database with said user interface whereby said messages are stored as data in said database and whereby said messages can be entered or accessed via said user interface.

35. The clinical workstation as recited in claim 34 wherein said user interface includes a dashboard on a computer screen, said dashboard comprising a palette with buttons representing said objects, persons, processes, services, operations or acts within said hospital.

36. The clinical workstation as recited in claim 34, wherein said set of generalized first tables comprise a standard, fixed and variable part.

37. The clinical workstation as recited in claim 36 wherein said standard part is determined by the type of operation, said fixed part is determined by a specific service, and said variable part is determined by said service.

38. The clinical workstation as recited in claim 34, further comprising procedures linked to said third tools for checking integrity of said messages.

39. A hospital information system stored on a network of computers and workstations comprising :

- a relational database stored on at least one computer of said network comprising :
  - a first set of tables with first columns and tuples containing first data, said first data being electronic messages being the contents of electronic forms;
  - a second set of tables with second columns and tuples containing second data, each of said second data representing at least one of said first data;

- a generator stored on at least one computer of said network comprising :
  - first tools supporting a user interface;
  - second tools accessing said database;
  - 5 - third tools implementing said electronic messages and linking said database with said user interface whereby said messages are stored as data in said database and whereby said messages can be entered or accessed via said user interface; and
- 10 - at least one clinical workstation comprising said user interface and modules allowing for entry of essences consisting of the group of processes, operations, services, acts and objects related to a patient's medical file within the hospital.
- 15 40. The hospital information system as recited in claim 39 further comprising data related to a patient's administrative file within the hospital.



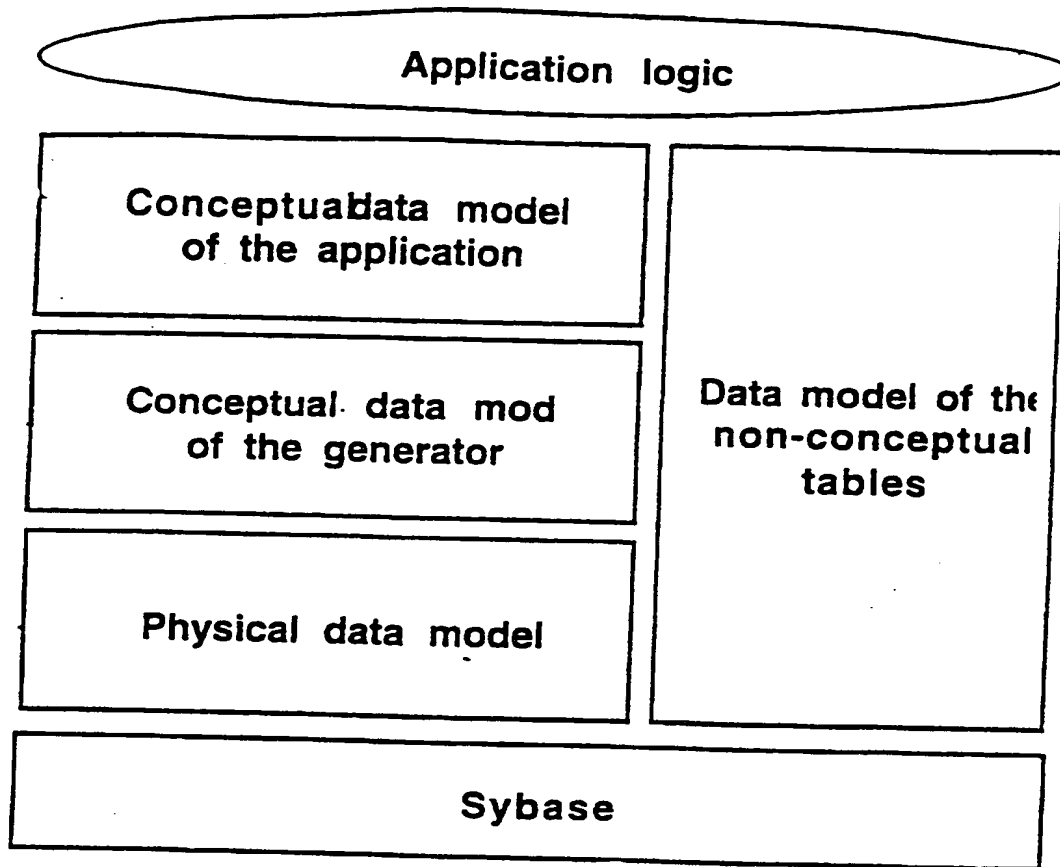


Figure 1. Data model architecture.